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Relating Energy Use to Economic Complexity

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Relating Energy Use to Economic Complexity

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Abstract

Relating Energy Use to Economic Complexity

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Energy is a fundamental requirement for the development of any complex human system. One prevalent view suggests that societal development is a direct result of increased energy use, such that progress occurs mainly during times when a surplus of energy is available. Alternately, anthropologist Joseph Tainter posits that human systems increase in complexity as a means of solving social problems, which requires additional energy use. Tainter's theory, since it implies compulsory increases in resource use, has significant implications for long-term economic sustainability. This thesis is an attempt to provide support, or show a lack thereof, for Tainter's theory. To accomplish this, the concept of entropy, in the context of information theory, is used as an indicator of economic complexity. Economic input-output tables for 40 countries from the World Input Output Database are used to calculate these metrics, on an annual basis between 1995 and 2011. Several model boundaries, on both the global and country scales, are used to select the data for these calculations. The results are compared to energy consumption and production data from the U.S. Energy Information Administration. This thesis presents the results of this comparison in the context of quantifying Tainter's theory of the linkage between energy and complexity.

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Chapter One: Introduction

Societies and economies, like any system, require energy to arise and thrive. High quality energy resources, in the proper technological context, allow useful work to be done at scales far greater than would be feasible with human labor alone. The substitution of energy and capital for labor has made great leaps forward possible, and fundamentally altered the structure of human society on several occasions over the course of history. While the importance of energy to any human system cannot be overstated, the nature of the relationship between energy availability and societal progress is complex and the subject of frequent debate. At most time scales we would concern ourselves with, fossil fuels are undeniably a limited resource, and one that carries significant risk with its use at current levels. As the more easily accessible fossil fuel sources become exhausted and further use entails both rising extraction costs and diminishing resource quality, questions naturally arise about societal and economic sustainability. Does a dwindling resource necessitate a declining society, or can technology substitute for energy, ensuring an ever-brighter future for humankind?

ENERGY AS A GROWTH-LIMITING FACTOR

There has long been a debate over the nature of the relationship between resource use and the economy. Energy consumption is likely a significant driver of economic growth, particularly in developed nations (Chontanawat et al., 2008), so the question is of the utmost importance. While some believe human ingenuity and the power of markets create an indefinitely sustainable economic system, others believe collapse is an inevitable outcome of using non-renewable resources for the production of energy.

Classical economists typically modeled the economy as a set of stocks with corresponding inflows and outflows (Boulding, 1973). In an economy at equilibrium, inflows balanced outflows, aided by the price-demand mechanism, and the economic system could persist indefinitely. Neoclassical economists view natural resources similarly to any other factor of production;

substitution of capital and improvements in technology are theorized to make up for a dwindling resource (Stiglitz, 1980).

Numerous objections to this optimistic outlook have been raised throughout history. Thomas Malthus (Malthus, 1798) raised the specter of a population outgrowing its resources, effectively providing an initial challenge to the idea that a state could progress without limit. More recently, the Limits to Growth report to The Club of Rome (Meadows et al., 1972) presented the results of an effort to model the interaction between human and natural systems. The results of the simulation indicated the possibility that exponential economic and population growth could lead to global collapse within a century. Even at current rates of use it is clear that fossil fuel deposits must eventually be exhausted or, more likely, reach a state where the cost of their extraction outweigh the benefits of their use. Since fossil fuels provide approximately 85% of the world's energy, limits to their availability, and the implications of those limits on economic growth, should be carefully considered (Benka, 2002).

Competing Views on Progress

One prevalent view of human history suggests that abundant energy is the primary driver of economic growth (Schurr, 1984), and that the complexity of economic systems evolves when there is a surplus of available energy. This is to say that complexity is a characteristic of human societies that we seek to increase, and which can only increase when energy is available in quantities beyond those required by the existing organizational structure.

There are several theoretical issues with this view. Operating from a Malthusian perspective, Boulding (Boulding, 1955) formulated the Dismal Theorem and the Utterly Dismal Theorem:

> If the only check to population is misery, the population will grow until it is miserable enough to check its growth. This is the Dismal Theorem. Furthermore, if the only check to population is misery, the result of any improvement is ultimately to enable a larger population than before to live in misery, so that resource-improvement actually increases the sum of misery. This is the Utterly Dismal Theorem.

The Utterly Dismal Theorem suggests that any available energy surplus will eventually be depleted by increases in population, rather than facilitating economic growth and increases in economic complexity. A growing population would require increasing net energy production on a per capita basis for surplus energy to be the driver of economic complexity.

The rebound effect, or Jevons' Paradox, acts in concert with the Dismal Theorem to compound the problem; increases in efficiency tend to be offset by increases in consumption. Basic economic principle suggests that increased energy or material efficiency must initially cause a decrease in overall consumption, but that decrease will lead to a drop in price and a corresponding increase in consumption over time (Jevons, 1865). This increase in consumption may be larger than the original resource savings, and may have a macroeconomic impact beyond the particular sector it originates in (Polimeni and Polimeni, 2006). This presents a serious roadblock to technology-driven schemes to reduce overall consumption of limited resources (Alcott, 2005). It is worth noting that the rebound effect has an analogue in the history of labor. "A consensus reigns that 'labour-saving' innovations did not save labour at all, but enabled, indeed, ever-increasing population and employment (Madlener and Alcott, 2009)", so the rebound effect may be seen as a special case of the Utterly Dismal Theorem.

In combination, the Utterly Dismal Theorem and rebound effect provide a powerful argument against the idea that economic complexity arises in response to energy abundance, suggesting that such abundance would be more than counterbalanced by increased consumption, whether per capita or gross. Moreover, subsistence societies would have had to build surpluses only with additional labor. Complexity for its own sake makes little sense, especially when that complexity must be the result of additional physical labor.

The anthropologist Joseph Tainter suggests that, rather than energy surpluses driving sociocultural and economic complexity, "complexity most commonly increases to solve problems, and compels increase in resource use (Tainter, 2011)". Since social problems are unavoidable, this would suggest that increased resource use is similarly compulsory. The implications of this idea for long-term economic sustainability are significant. If complexity must increase, so must resource use, leaving resource conservation as a nonsensical and ineffective means to ensure sustainability. Moreover, price-based conservation measures will be similarly ineffective over a long enough period.

Tainter's theory is certainly compelling, and critical to our economic path forward if true, but it is largely based on historical and qualitative analysis. Quantitative substantiation of the theory, based on modern data, is highly desirable. This thesis is largely an attempt to provide such support, or show a lack thereof.

To begin the quantitative analysis of a qualitative hypothesis, appropriate metrics that relate postulates to conclusions must be adopted. Stated simply, Tainter's theory is that cultural complexity increases in response to the necessity of solving social problems, and that this requires additional energy use. This is an explicit statement about causation, rather than simply correlation, so simply showing that complexity and energy use are related, while useful, is not tantamount to confirmation. Thankfully, Tainter goes further and states that energy surpluses only very rarely drive increases in complexity, so an absence of correlation between surplus and complexity would be of some importance.

According to Tainter, "Complexity is generally understood to refer to such things as the size of a society, the number and distinctiveness of its parts, the variety of specialized social roles that it incorporates, the number of distinct social personalities present, and the variety of mechanisms for organizing these into a coherent, functioning whole"(Tainter, 1990). Inequality and heterogeneity are fundamental components of complexity (Blau, 1977). Societies that exhibit greater inequality and heterogeneity are more economically and structurally differentiated, which corresponds to greater complexity.

There are a variety of ways to quantify complexity, but Tainter's discussion of the subject suggests that the most useful metric will be one that indicates heterogeneity or structural complexity, and is larger when a system contains a number of pseudo-independent sub-systems. As will be discussed below, entropy in the context of information theory forms the basis of one such measure.

ENTROPY

In a general sense, entropy can be thought of as a measure of disorder, or randomness in a system. Entropy is a concept with roots in thermodynamics and statistical mechanics, which has been applied to numerous other fields of inquiry through mathematical analogy (Pierce, 1980). While it is useful to understand the original concept of entropy as applied to physics, it is not clear that the concept retains all of its meaning when applied to other fields, though some researchers have based large bodies of work on the idea that it does (Ayres, 1997). The following discussion of physical or thermodynamic entropy should serve mainly to shed some light on how the term is defined mathematically. The divergence between the characteristics of physical entropy and those of the concept as it will be used for analysis in this thesis will be made explicit when necessary for clarity.

Physical entropy is typically described in relation to a body of gas in a sealed container, divided in two, with all of the gas on one side of the divider. If the divider were to disappear, the gas would move to occupy the entire container. While we could originally state with a high degree of certainty that all of the particles in the gas could be found on one side of the divider, we would only be able to say that they could be found somewhere in the whole container once the divider was removed. With the divider removed, the entropy of the system has increased and our uncertainty about the position of the gas particles has increased. From this example, we can see that the physical concept of entropy is associated with uncertainty. Further, processes that yield increased entropy of this sort are irreversible.

Boltzmann expressed entropy as:

$$S = KlogW \tag{1}$$

where S is the entropy, W is the thermodynamic probability, or the number of possible microstates associated with a particular system macrostate, and K is an arbitrary constant (Gatlin, 1972). The concepts of macrostates and microstates are fundamental to this definition, and can be understood by thinking of, for example, a series of three switches. Each switch can be in one of two states: on or off. Without identifying specifically which switches are on and which are off, stating that two switches are on and one is off is to identify the macrostate. Stating that the first switch is off and the next two are on is to identify the microstate. In other words, the macrostate identifies the *number of elements* of a system in each possible state, while the microstate identifies the states of *each specific element*. Note that several microstates can produce the same macrostate: the first switch can be off, the second switch can be off, or the third switch can be off. Thus, the thermodynamic probability, W, can be formally expressed by:

$$W = \frac{N!}{N_1!\,N_2! \cdots N_i!} \tag{2}$$

where N is the number of system elements (particles, switches, etc.), m is the number of possible states (two, in the case of the switch example), and N_i is the number of elements in the ith state (Bonchev and Rouvray, 2003).

Information Theory

Claude Shannon (Shannon, 1948), in developing a mathematical theory of communication, proposed the definition of entropy most relevant to the topic of this thesis:

$$H = -K \sum_i P_i log P_i \tag{3}$$

where p_i is the probability some event will occur, and K is again an arbitrary constant. This measure of entropy is mathematically identical to the expectation associated with Boltzmann's entropy, with p_i as the probability that a particular microstate is responsible for a known macrostate. The maximum possible value of H occurs when all events are equiprobable (Gatlin, 1972), and is expressed as:

$$H^{max} = \log(m) \tag{4}$$

where m is the number of possible outcomes for an event. Shannon's formula effectively quantifies the uncertainty, or indeterminacy, of a particular system (Ulanowicz, 1997). In the case where probabilities are equal for all events, it is impossible to predict which event will occur with any accuracy, and the system is maximally indeterminate. Somewhat non-intuitively, this same situation is also said to have the highest information content. In a system where all outcomes are known *a priori*, resolution of the events yields no new information, whereas resolution of equiprobable events yields the greatest possible amount of new information. Thus, "Shannon's measure of uncertainty, which he called entropy, measures how much is expected to be learned about a question when all that is known is a set of probabilities (Tribus and McIrvine, 1971)".

As mentioned above, there are some notable ways in which Boltzmann's entropy differs from Shannon's entropy. By the Second Law of Thermodynamics, the entropy of a closed system can only increase, so any process that increases entropy in such a system is fundamentally irreversible. This is, of course, not necessarily true for Shannon's entropy; occurrence probabilities for the events in a system may change such that the Shannon entropy decreases over time. However, Nicholas Georgescu-Roegen (Georgescu-Roegen, 1971) argued that the Second Law of Thermodynamics, or Entropy Law, applies to economics in much the same way it does to physics. According to Georgescu-Roegen, low entropy resources allow for economic growth, and are converted to higher entropy resources once used. In this fashion, assuming the Earth is a relatively closed system, inherently finite energy and material resources become unusable, and growth ceases. This is similar to Tainter's concept of energy gain, where high-gain systems result from the use of abundant, high-quality resources in the proper technological context (Tainter et al., 2003). The common reply to the notion of the Entropy Law as a limiting factor on economic growth is to note that the Earth is not a closed system and that, in fact, it constantly receives a great deal of solar energy as an exogenous input.

ULANOWICZ'S METRICS

Robert E. Ulanowicz et al (Ulanowicz et al., 2009) use the fundamental concepts of Information Theory to derive a set of metrics pertaining to the performance and stability of a system. Specifically, Ulanowicz analyzed the movement of carbon between various species in an ecosystem, but the metrics he proposed could be used to describe any system that consists of a network of nodes, with some flow between those nodes. From Shannon's theorem, we can define the indeterminacy of a particular event, p_i, as:

$$h_i = -kp_i \log(p_i) \tag{5}$$

It is apparent that when p_i is close to 0, and the event is almost certain not to occur, h_i is closer to 0. When p_i is close to 1 and the event is almost certain to occur, h_i is again close to 0. Larger values of h_i are yielded by intermediate values of p_i, with a maximum value at a p_i of e^{-1}. Ulanowicz interprets h_i as the capacity of an event to change a system. Extremely common events and extremely rare events are both unlikely to change a system over time, as the system is likely stabilized for common occurrences, and rare occurrences, though they may individually hold great influence, do not occur often enough. The aggregate indeterminacy for an entire system, H, is the sum of individual h_i values, which has the same form as Shannon's measure of entropy, and can be viewed as the capacity of the entire system to undergo change.

Since flows from one node to another are involved, it is useful to describe the entropy based on the joint probability, p_{ij}, that an amount of some medium will flow from node i to node j. Ulanowicz calls this the "average mutual constraint", and defines it as:

$$X = k \sum_{i,j} p_{ij} log\left(\frac{p_{ij}}{p_{i.}p_{.j}}\right) \tag{6}$$

where $p_{i.}$ is the probability that flow from node i occurs to any node j, and $p_{.j}$ is the probability that node j receives flow from any node i. Further, Ulanowicz defines "conditional entropy" as:

$$\psi = H - X \tag{7}$$

such that ψ is the divergence of the described system from a state where all probabilities are independent.

These metrics can be formulated in terms of flow quantity, instead of flow probability, with some fairly simple substitutions. For some matrix of flows, *T*, let T_{ij} be the flow from node *i* to node *j*, $T_{i.}$ be the total flow out of node *i*, $T_{.j}$ be the total flow into node *j*, and $T_{..}$ be the sum of all flows in the system, or "total system throughput". The probabilities discussed above can now be represented as ratios of these quantities:

$$p_{ij} \sim \frac{T_{ij}}{T_{..}} \quad p_{i.} \sim \frac{T_{i.}}{T_{..}} \quad p_{i.} \sim \frac{T_{.j}}{T_{..}} \tag{8}$$

Substituting these relationships, the entropy metrics can be written as:

$$H = -k \sum_{i,j} \frac{T_{ij}}{T_{..}} log\left(\frac{T_{ij}}{T_{..}}\right) \tag{9}$$

$$X = k \sum_{i,j} \frac{T_{ij}}{T_{..}} log\left(\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right) \tag{10}$$

$$\psi = -k \sum_{i,j} \frac{T_{ij}}{T_{..}} log\left(\frac{T_{ij}^2}{T_{i.}T_{.j}}\right) \tag{11}$$

Ulanowicz argues that *H* is a system's "capacity for evolution or self-organization", and that its two components, *X* and ψ, represent what is "regular, orderly, coherent, and efficient", and what is "irregular, disorderly, incoherent, and inefficient" about the system, respectively (Ulanowicz et al., 2009). Moreover, both X and ψ are required elements of a robust system.

Multiplying each of these metrics by the total system throughput yields three additional metrics, “capacity” (C), “ascendancy” (A), and “reserve” (ϕ), which give a better sense of the scale of the system in question:

$$C = T_{..}H \quad A = T_{..}X \quad \phi = T_{..}\psi \tag{12}$$

Capacity represents the ability of a system to evolve and develop, and is the sum of ascendency and reserve. Ascendency is the ability of a system to maintain itself as a cohesive whole, while reserve is a measure of its ability to react to unanticipated changes. A balance of the two characteristics is required for the long-term stability of a system. Systems that have low ascendency have “neither the extent of activity nor the internal organization needed to survive,” while systems without adequate reserves are “prone to collapse in the face of even minor novel disturbance” (Ulanowicz et al., 2009).

Ulanowicz’s metrics are defined for closed systems, where no exogenous inputs and outputs are present. They can be corrected to describe open systems with the addition of the term described by Equation 11, where the new total system throughput is defined by equation 12.

$$O = -\sum_{j} \frac{T_{input,j}}{T_{..}} log\left(\frac{T_{input,j}}{T_{.j}}\right) - \sum_{i} \frac{T_{i,output}}{T_{..}} log\left(\frac{T_{i,output}}{T_{i.}}\right) \tag{13}$$

$$T_{..} = \sum_{i,j}\left(T_{i,j} + T_{input,j}\right) \tag{14}$$

The ascendancy and reserve metrics are modified simply through addition of the term *O*. Since capacity is the sum of these two terms, twice the quantity *O* is added to express open system capacity.

$$C' = C + 2(O) \quad A' = A + O \quad \phi' = \phi + O \tag{15}$$

Two additional metrics based on the main Ulanowicz metrics are potentially useful for this analysis (Ulanowicz, 2002; Zorach and Ulanowicz, 2003). The number of roles, *n*, and the effective connectivity, *m*, can be expressed as:

$$n = 2^{X} \tag{16}$$

$$m = 2^{\frac{\psi}{2}} \tag{17}$$

The number of roles is a measure of the average number of transfers an input goes through in a system before it becomes an output. Effective connectivity describes the average number of links per node in a network.

The normalized average mutual constraint is known as the relative entropy:

$$\hat{X} = \frac{X}{\log(a)} \tag{18}$$

where *a* is the number of flows in the system, and *log(a)* represents the maximum entropy, or information content, corresponding to equiprobability or equal magnitude for each flow (Gatlin, 1972). The relative entropy metric includes information about both the divergence of the flows in the system from equiprobability and from independence. On its own, X contains no information about its maximum value, and is defined for all real, positive numbers. Normalizing X to the maximum entropy value for the system produces a useful scaled metric that contains, implicitly, information about the size of the system in question.

INPUT-OUTPUT ANALYSIS

Ulanowicz's formulations of Shannon's entropy allow for the determination of summary statistics describing the complexity of a network of flows. Input-output tables, of the type described by Wassily Leontief (Leontief, 1986), represent one such network of flows suitable for this kind of analysis. In general, an input-output table consists of rows of producers and columns of consumers, with table entries that correspond to the amount, typically reported as a monetary value, of a particular producer's product that a particular consumer purchases and uses. Additional columns contain data for final sales to government and private consumers.

Input-output tables contain a high-level view of the structure of an economy, and the information entropy concept provides a useful way to summarize this structure. Normalizing the individual flows represented in an input-output table to the total flow throughout the system allows for the application of Shannon's entropy concept. Numerous workers have used information entropy in concert with input-output tables for a variety of applications, including the determination of optimal industry group aggregation, and interpolation of missing time series data (Theil and Uribe, 1967; Batten, 1983).

COMPLEXITY

Shannons's information entropy has been employed in numerous fields as a basis for the quantitative representation of complexity (Bonchev and Rouvray, 2003; Mowshowitz and Dehmer, 2012). As discussed previously, information entropy is a measure of the information content, and "The complexity of an object such as a machine, or an organism, is essentially equivalent to its *information content*." (Ayres, 1998). Conceptually, this is fairly simple; computer code that executes a more complex function typically requires more lines of code and a manual to assemble a more complicated piece of machinery requires more individual instructions. Higher information content describes a more complex system.

Ulanowicz's metrics provide a framework to more thoroughly describe the complexity of a system. The aggregate indeterminacy, H, of a system is the maximum information content for the system, given the known flows. It assumes complete independence for all flows. The average mutual constraint, X, is a bivariate measure of the entropy, or measure of the interdependence of the flows (Theil, 1967). The conditional entropy, ψ, is the difference between the two, and is a measure of the system's divergence from complete flow independence. While the indeterminacy is a measure of a hypothetical state, the average mutual constraint, and its throughput-scaled counterpart ascendancy, are likely more accurate representations of the actual system state. Ulanowicz states:

> Briefly, the major attributes of more developed ecosystem networks are a larger number of species, higher degree of cycling within the system, increased efficiency of the components, and greater specialization of the components. Each of these properties is capable of increasing the ascendancy of the network. More compartmentalization leads to a higher entropy, thus raising the upped bound on the ascendancy. The ascendancy reaches its upper limit under the ideal conditions when the medium is cycled around a single loop with no losses (Ulanowicz and Hirata, 1984).

As an indicator of diversity, efficiency, specialization, and compartmentalization, ascendancy, or its un-weighted counterpart average mutual constraint, would seem to be an ideal indicator of overall system complexity. Other workers have noted that the DNA of more complex organisms can be classified as having higher conditional entropy values (Gatlin, 1972).

Further, it is apparent the number of roles and connectivity in the system, as calculated by equations 14 and 15, represent distinct elements of a system's overall complexity. Increases in either measure may represent an increase in complexity, and a complex system requires both qualities. Systems with maximum connectivity between very few roles, or many unconnected roles cannot be thought of as complex. Maximum connectivity occurs when all flows in a system are equiprobable, and the aggregate system indeterminacy and conditional entropy (equations 7 and 8) are equal to the maximum information entropy for the system. In this case, mutual constraint (equation 9) is zero and there is only one effective role in the system. Conversely, the maximum number of roles exist in a system where all flows are independent, and conditional entropy is zero. This yields a system where nodes are effectively connected to only one other node. In either extreme case, the complexity of the system described is conceptually somewhat ambiguous. A system composed entirely of unique nodes connected in series can in some ways be considered rather simple, as little information is required to describe its structure. However, describing the constituents of the system requires more information than it would if some nodes occupied the same roles. Thus, maximal link density or number of roles represent neither maximal overall complexity nor minimal overall complexity.

UNITS

Un-weighted Ulanowicz metrics H, ψ, and X are expressed in units determined by the base of the logarithm used in their calculation. For this analysis, base-two logarithms are used, so results are in bits. A bit is the "information inherent in a single binary decision" (Ulanowicz, 1997). Weighted metrics C, ϕ, and A are equal to the un-weighted metrics multiplied by total system throughput, so they are expressed in dollar-bits. As an absolute measure, these units are meaningless, but will function for comparison of models and data in time series.

Chapter Two: Data and Methods

DATA

The main data for this thesis are from the World Input-Output Database (WIOD), a synthesis of national input-output tables into a time series of tables representing industry-by-industry trade for the world (Timmer et al., 2012). The World Input-Output Tables (WIOT) that comprise much of the WIOD are constructed from national Supply-Use Tables or Input-Output Tables, United Nations National Accounts industrial output and consumption data, and international trade data. National data sources are indicated in Appendix A. It should be noted that, while The WIOD contains data on a yearly basis, data is only available at irregular intervals for many of the included countries. In the case of missing data, National Accounts statistics are used for interpolation. Further, harmonization of data sources to a common standard involved a combination of product and industry classification, aggregation by product and industry, and adjustments based on reference year and price concept.

The WIOD includes WIOTs for each year from 1995 to 2011. Data are included for products in 35 industries, produced and consumed by 40 countries. The countries selected are 27 members of the European Union and 13 other major nations throughout the world, that collectively account for more than 85 percent of the global Gross Domestic Product (Timmer et al., 2012). These countries, along with the ISO 3166-1 alpha-3 country codes they are listed under in the WIOD, are identified in Table 1 below.

European Union			North America	Asia and Pacific
Austria (AUT)	Germany (DEU)	Netherlands (NLD)	Canada (CAN)	China (CHN)
Belgium (BEL)	Greece (GRC)	Poland (POL)	United States (USA)	India (IND)
Bulgaria (BGR)	Hungary (HUN)	Portugal (PRT)	Mexico (MEX)	Japan (JPN)
Cyprus (CYP)	Ireland (IRL)	Romania (ROU)		South Korea (KOR)
Czech Republic (CZE)	Italy (ITA)	Slovak Republic (SVK)	**South America**	Australia (AUS)
Denmark (DNK)	Latvia (LVA)	Slovenia (SVN)	Brazil (BRA)	Taiwan (TWN)
Estonia (EST)	Lithuania (LTU)	Spain (ESP)		Turkey (TUR)
Finland (FIN)	Luxembourg (LUX)	Sweden (SWE)		Indonesia (IDN)
France (FRA)	Malta (MLT)	United Kingdom (GBR)		Russia (RUS)

Table 1: List of countries in WIOD, with ISO 3166-1 alpha-3 country codes

The WIOD also includes data for the Rest of the World (RoW), which is modeled due to insufficient data sources for many of the countries not explicitly included in the WIOD. Imports and exports for the RoW are derived residually, and its input-output structure is modeled as that of an average developing country.

The industries included in the WIOD are listed in Table 2. Theses 35 industries are aggregated from 59 products present in the supply-use tables used in the creation of each WIOT. Though they are the result of aggregation, use of the WIOT data requires the assumption that each industry produces only one unique product.

NACE Code	Description of Industry	WIOT Column
AtB	Agriculture, Hunting, Forestry and Fishing	c1
C	Mining and Quarrying	c2
15t16	Food, Beverages and Tobacco	c3
17t18	Textiles and Textile Products	c4
19	Leather, Leather and Footwear	c5
20	Wood and Products of Wood and Cork	c6
21t22	Pulp, Paper, Paper , Printing and Publishing	c7
23	Coke, Refined Petroleum and Nuclear Fuel	c8
24	Chemicals and Chemical Products	c9
25	Rubber and Plastics	c10
26	Other Non-Metallic Mineral	c11
27t28	Basic Metals and Fabricated Metal	c12
29	Machinery, Nec	c13
30t33	Electrical and Optical Equipment	c14
34t35	Transport Equipment	c15
36t37	Manufacturing, Nec; Recycling	c16
E	Electricity, Gas and Water Supply	c17
F	Construction	c18
50	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	c19
51	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	c20
52	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	c21
H	Hotels and Restaurants	c22
60	Inland Transport	c23
61	Water Transport	c24
62	Air Transport	c25
63	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	c26
64	Post and Telecommunications	c27
J	Financial Intermediation	c28
70	Real Estate Activities	c29
71t74	Renting of M&Eq and Other Business Activities	c30
L	Public Admin and Defence; Compulsory Social Security	c31
M	Education	c32
N	Health and Social Work	c33
O	Other Community, Social and Personal Services	c34
P	Private Households with Employed Persons	c35

Table 2: List of industries in WIOD, with Nomenclature of Economic Activities (NACE) codes

The general structure of a WIOT can be seen in Figure 1. Rows indicate producers, while columns indicate consumers, both by industry and country. A cell in the table represents the value of the products flowing from a producer to a consumer. Industry to industry flow is considered intermediate use, where products from one industry are used to create the products of another. Final use is also included in the table, as purchases by private and government consumers.

		Country A Intermediate *Industry*	Country B Intermediate *Industry*	Rest of World Intermediate *Industry*	Country A Final domestic	Country B Final domestic	Rest of World Final domestic	Total
Country A	*Industry*	Intermediate use of domestic output	Intermediate use by B of exports from A	Intermediate use by RoW of exports from A	Final use of domestic output	Final use by B of exports from A	Final use by RoW of exports from A	Output in A
Country B	*Industry*	Intermediate use by A of exports from B	Intermediate use of domestic output	Intermediate use by RoW of exports from B	Final use by A of exports from B	Final use of domestic output	Final use by RoW of exports from B	Output in B
Rest of World (RoW)	*Industry*	Intermediate use by A of exports from RoW	Intermediate use by B of exports from RoW	Intermediate use of domestic output	Final use by A of exports from RoW	Final use by B of exports from RoW	Final use of domestic output	Output in RoW
		Value added	Value added	Value added				
		Output in A	Output in B	Output in RoW				

Figure 1: General structure of a World Input-Output Table, from Timmer (2012)

Payments for labor, capital, and government are included at the bottom of the intermediate use section of the table. Summing over a column associated with a particular industry in a particular country will yield the same result as summing over the row associated with that industry. It is fundamental to the concept of an input-output table that the total value of an industry's output equals the total cost of the resources it procured to make that output.

Energy consumption, energy production, emissions, and population data used in this thesis are from the U.S. Energy Information Administration. Annual data from 1995 through 2011 are used for comparison to calculated complexity metrics. Time series plots of total primary energy consumption and production, in quadrillion BTU, are shown in Figure 2.

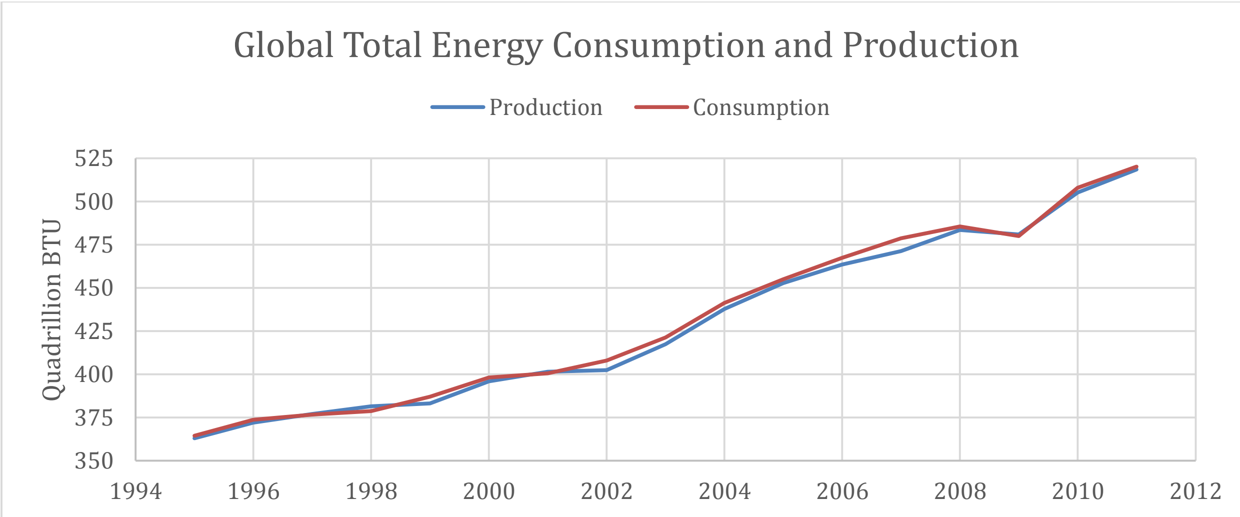


Figure 2: Time series of global total energy consumption and production from 1995 to 2011

Figures 3 and 4 show total primary energy production by WIOD country. The RoW world values were obtained by subtracting the sum of the production for the WIOD countries from the total global production shown in Figure 2.

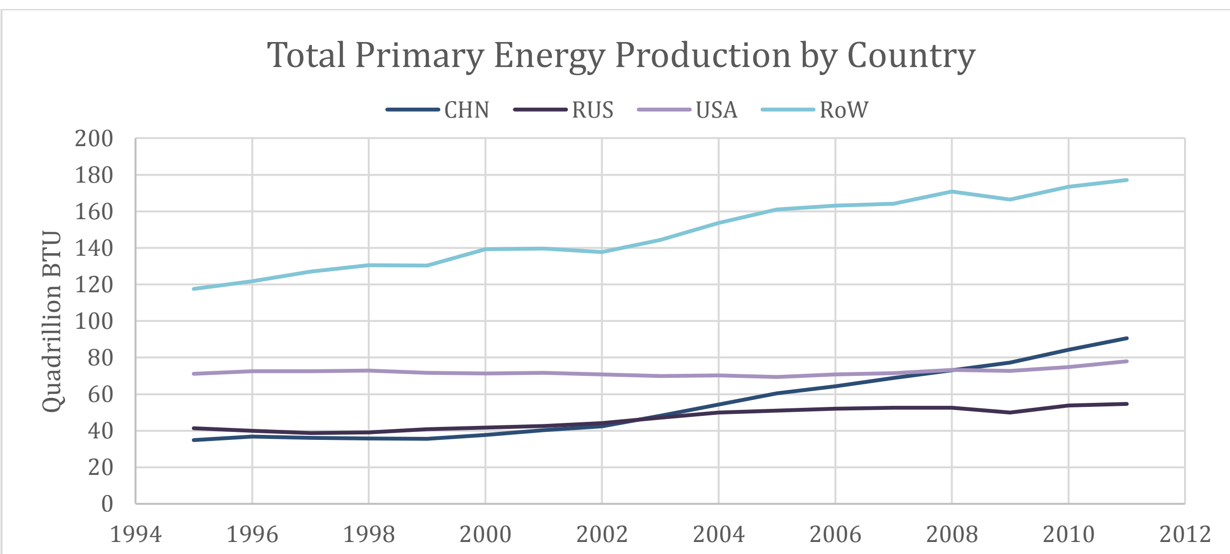


Figure 3: Time series of total primary energy production for top producing countries and rest of world from 1995 to 2011

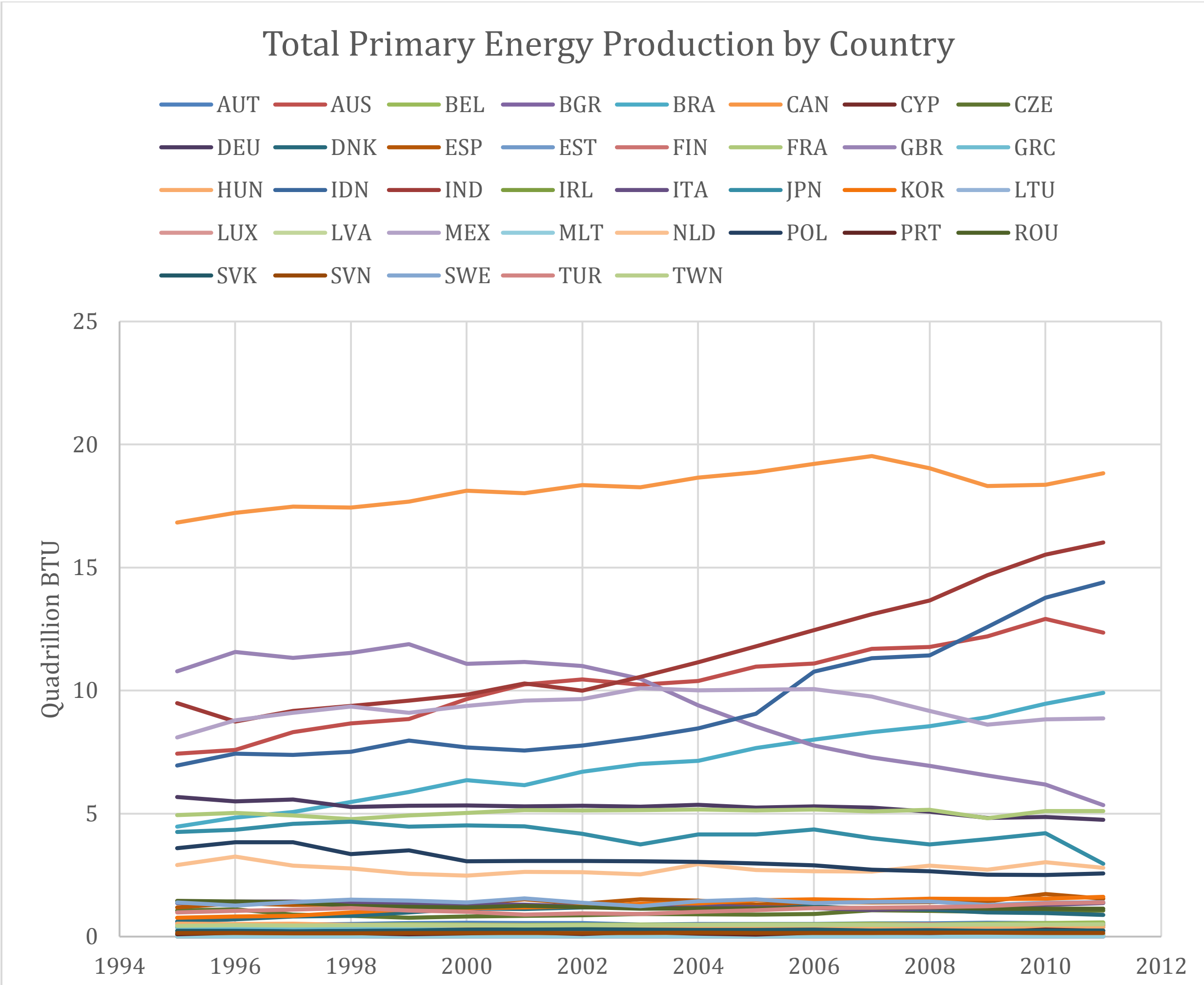


Figure 4: Time series of total primary energy production for mid and low producing countries from 1995 to 2011

Figures 5 and 6 show total primary energy consumption by WIOD country. Again, the value for the rest of the world is calculated.

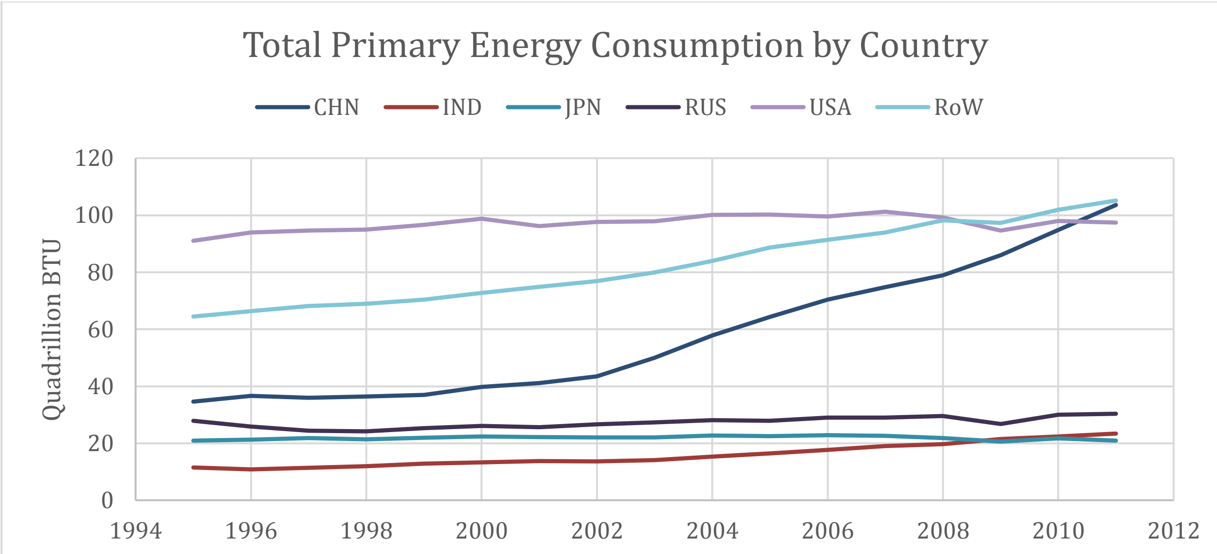


Figure 5: Time series of total primary energy consumption for top producing countries and rest of world from 1995 to 2011

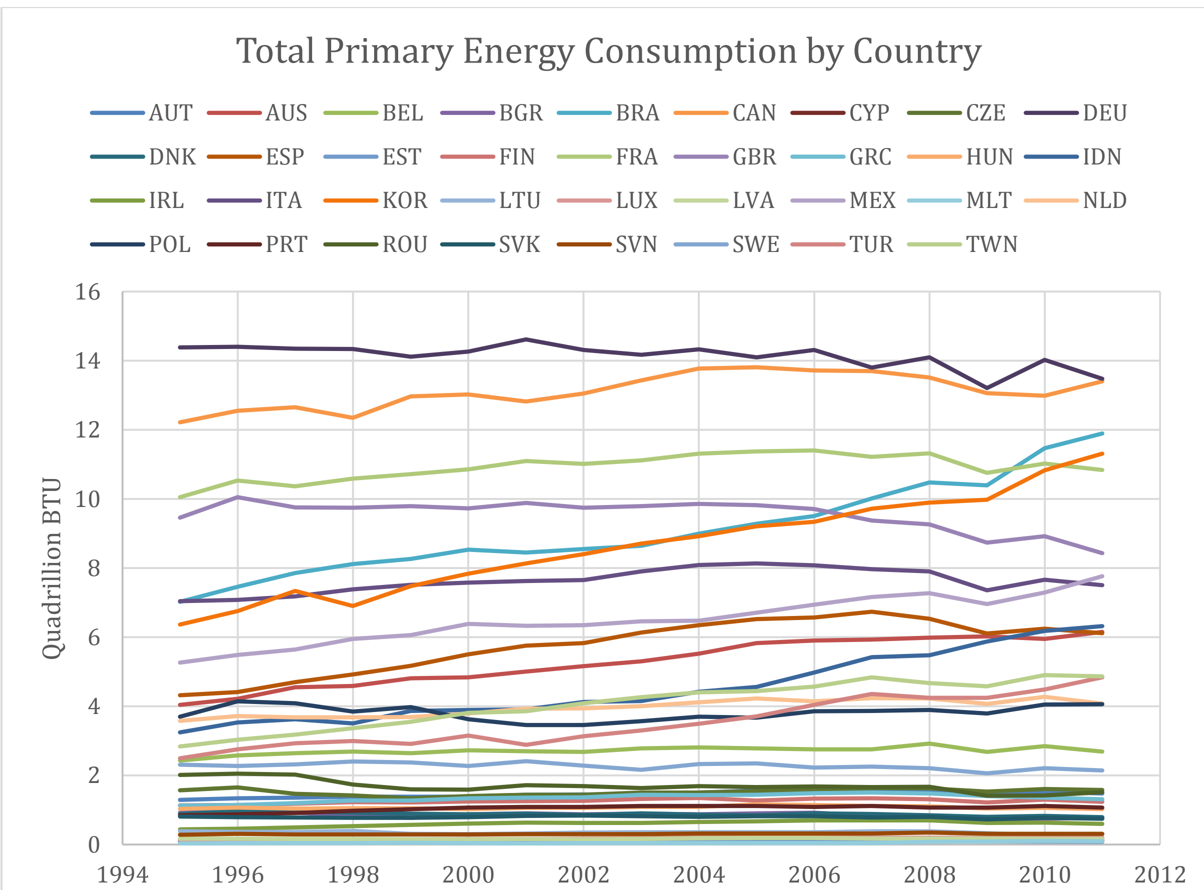


Figure 6: Time series of total primary energy consumption for mid and low producing countries from 1995 to 2011

Figure 7 shows Total Primary Energy Consumption per capita. Canada, Luxembourg, and the United States consistently have the highest per capita consumption, at values exceeding 300 million BTU per person. India's per capita consumption is consistently the lowest of all WIOD nations, at values between 12 and 20 million BTU per person.

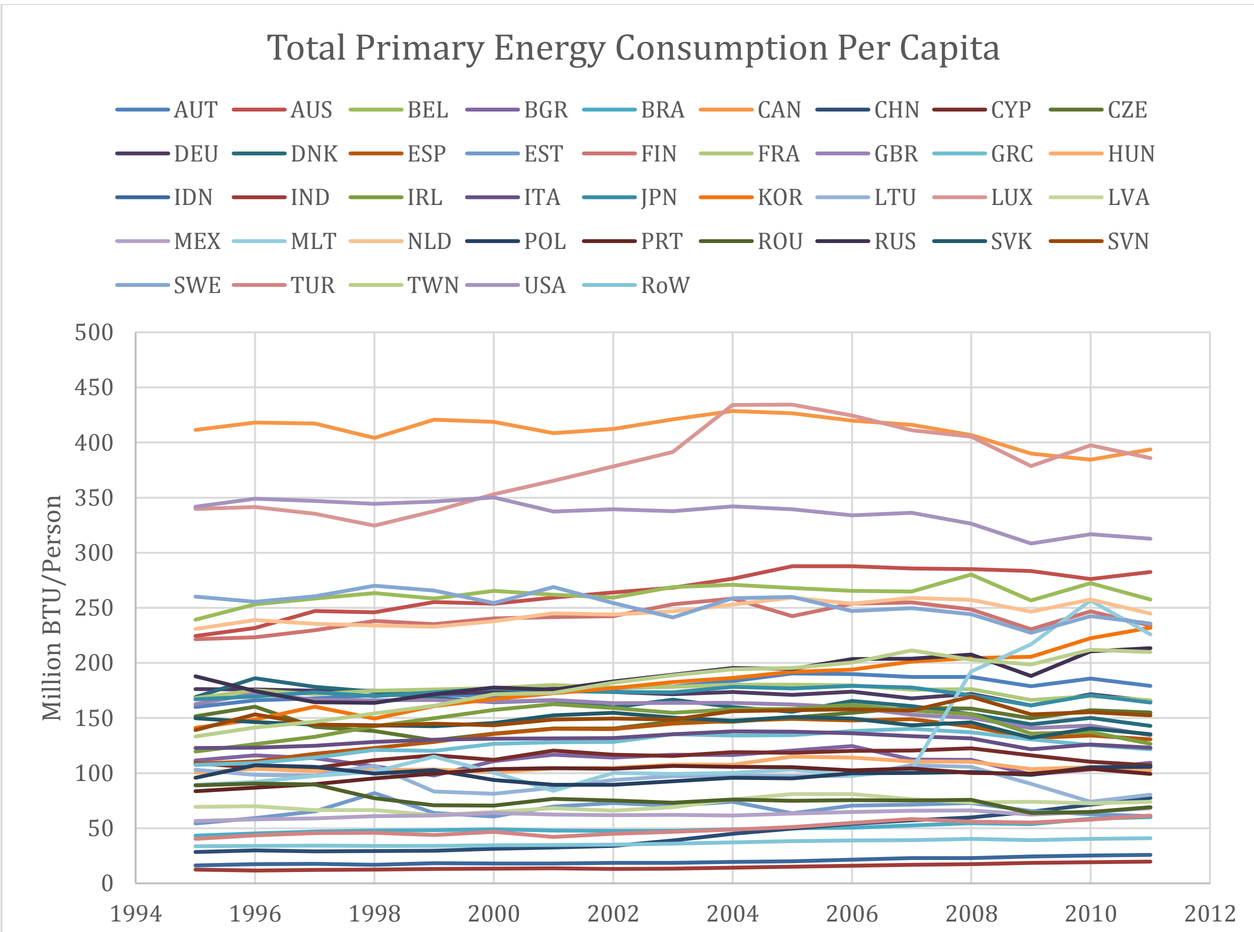


Figure 7: Time series of total primary energy consumption per capita from 1995 to 2011

Figures 8 and 9 show net total primary energy production normalized to total energy production (production minus consumption, divided by production) for each country. Cyprus, Malta, Estonia, and Luxembourg are excluded from these figures, since they typically have no production, or production values so low as to produce very large negative numbers. Additionally, Figure 9 excludes countries with net consumption values greater than three times their total energy production, as to allow better visual distinction between the bulk of countries with less extreme values. Ireland, Taiwan, Italy, Spain, Japan, South Korea, Latvia, and Portugal have the most negative normalized net production values. Australia, Canada, Indonesia, Mexico, Russia, and the rest of the world (RoW) are net producers for every year from 1995 to 2011. The United Kingdom moved from being a net producer to a net consumer in 2004, and Denmark went from being a net consumer to a net producer in 1999.

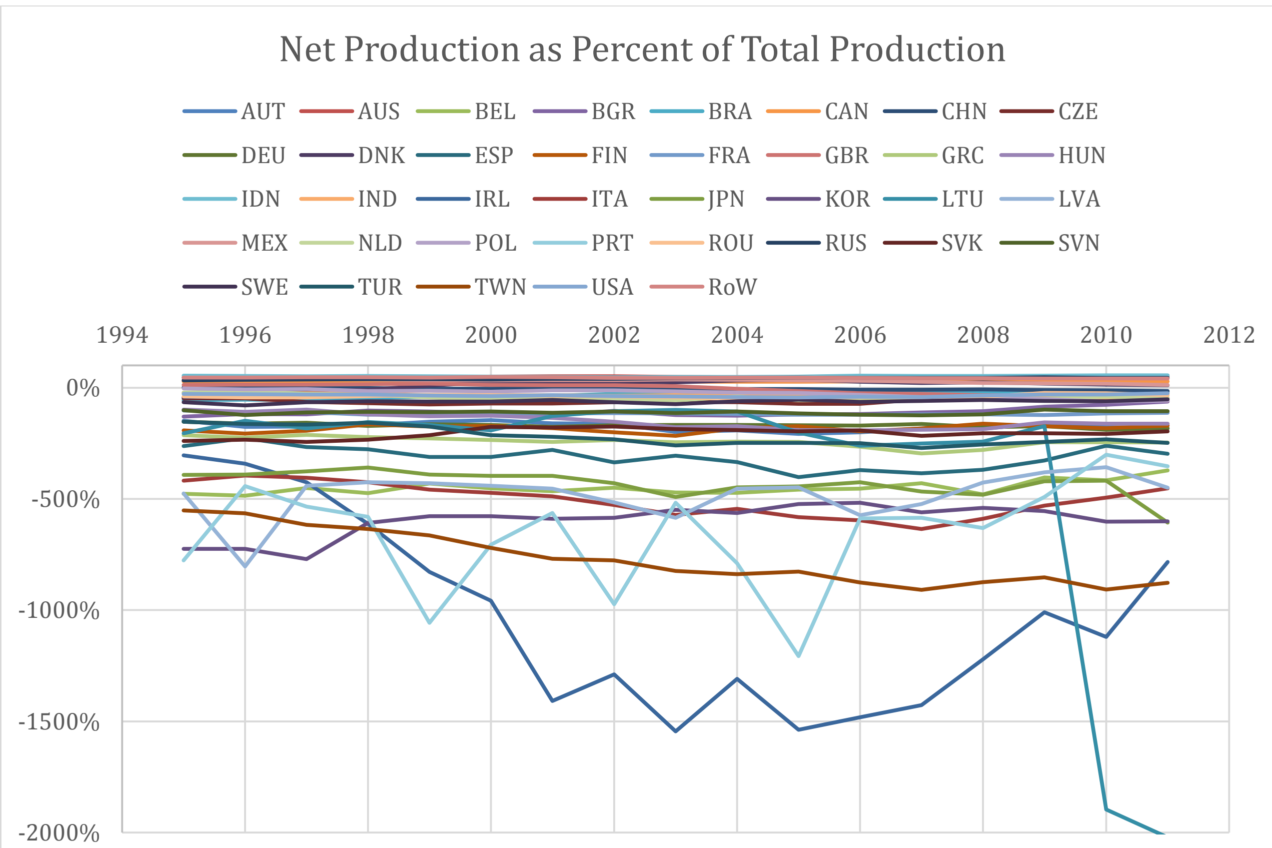


Figure 8: Time series of net primary energy production normalized to total primary energy production from 1995 to 2011. Cyprus, Estonia, Malta and Luxembourg excluded.

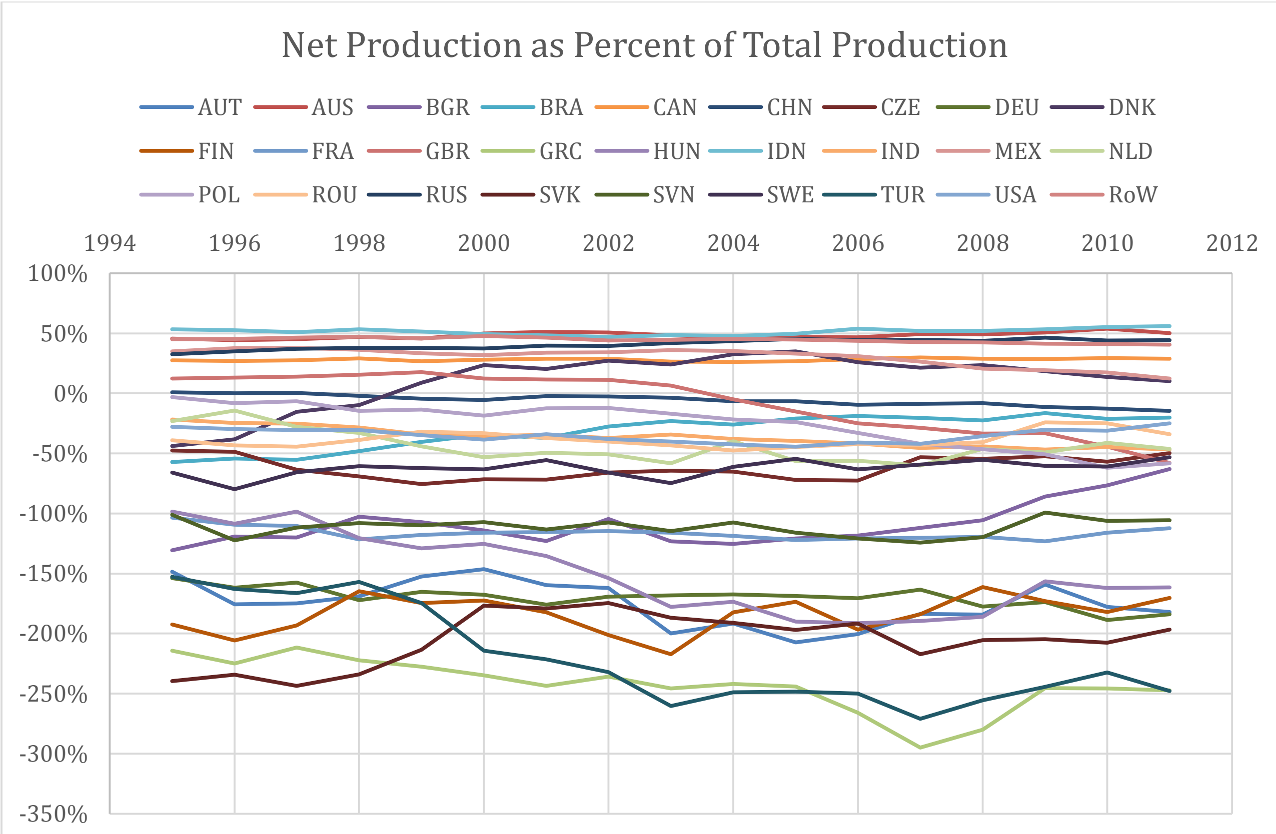


Figure 9: Time series of net primary energy production normalized to total primary energy production from 1995 to 2011. No countries with net consumption greater than 3 times their production are shown.

The data from the Energy Information Administration cover significantly more countries than are explicitly included in to WIOD. On average The WIOD countries, not counting the RoW, account for 81 percent of global total primary energy consumption, and 66 percent of global total energy production. Figure 10 is a time series showing the change in the percent of consumption and production accounted for by the WIOD countries. A general decreasing trend can be seen in the consumption statistic, which means that countries not explicitly included in the WIOD are consuming an increasing percentage of the world's total energy supply. This is confirmed by the increasing trend in the RoW energy consumption seen in figures above.

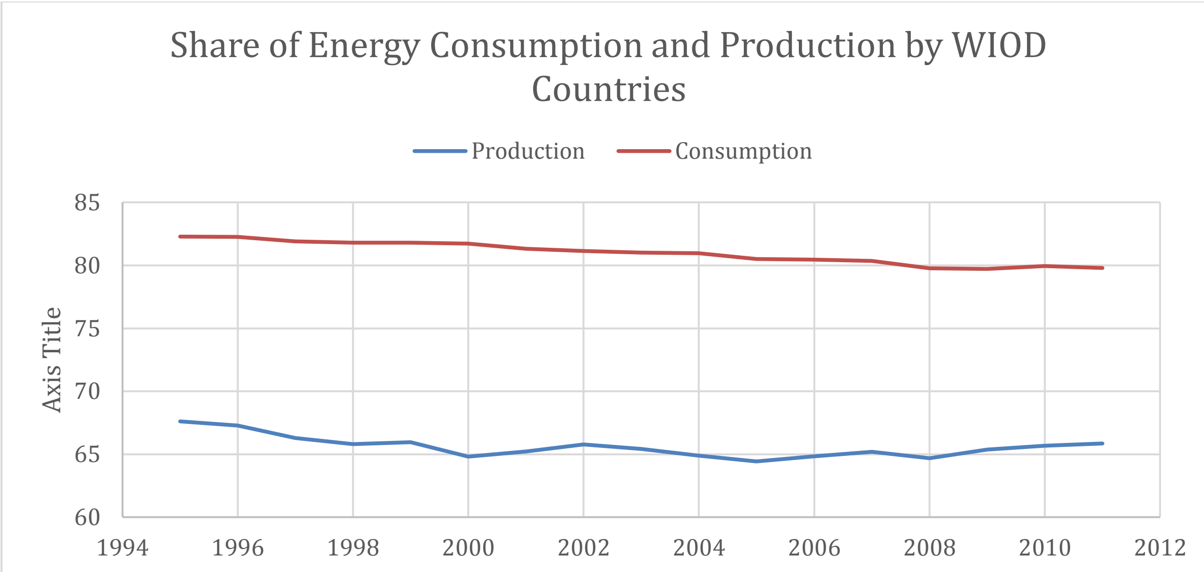


Figure 10: Time series of percent of total global production and consumption accounted for by WIOD countries from 1995 to 2011

Methods

Ulanowicz metrics were calculated from WIOT data with a series of MATLAB scripts. These scripts are included in Appendix C. Each script is fundamentally a tool to select the pertinent cells from the raw WIOT data in Microsoft Excel table format, and calculate the metrics on a cell-by-cell basis. They differ primarily in the cells they select. The data model of interest determines the desired cells. Six models are considered in this analysis. These models are summarized in Table 3 and described in detail below.

Model Name	Data Included	Reporting Level	Calculation Method
Open Global	All intermediate flows	World	All data treated as endogenous
Closed Global	All intermediate, final use, and value added flows	World	All data treated as endogenous
Global Input-Output	All intermediate, final use, and value added flows	World	Value added treated as exogenous input. Final use treated as exogenous input.
Open Domestic	Only domestic intermediate flows	Country	All data treated as endogenous
Closed Domestic	Domestic intermediate, final use, and value added flows	Country	All data treated as endogenous
Domestic Input-Output	Domestic intermediate, final use, and value added flows	Country	Value added treated as exogenous input. Final use treated as exogenous input.

Table 3: List of models used for analysis of WIOT data

The most basic model includes the intermediate flow data for each country in the WIOD and the rest of the world (RoW). Only flows from industry to industry are considered endogenous in this case. This model is considered open, since there are flows not included that could be considered exogenous in other analyses. The Ulanowicz metrics are calculated at the global level. The data uses in this model are indicated in Figure 11.

		Country A I1 I2 I3 I4	Country B I1 I2 I3 I4	Rest of World I1 I2 I3 I4	Country A Final Use	Country B Final Use	Rest of World Final Use	Total Output
Country A	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use of Domestic Product	Intermediate Use by Country B of Exports from A	Intermediate Use by RoW of Exports from B	Final Use of Domestic Product	Final Use by Country B of Exports from A	Final Use by RoW of Exports from B	Output from A
Country B	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use by Country A of Exports from B	Intermediate Use of Domestic Product	Intermediate Use by RoW of Exports from B	Final Use by Country A of Exports from B	Final Use of Domestic Product	Final Use by RoW of Exports from B	Output from B
Rest of World	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use by Country A of Exports from RoW	Intermediate Use by Country B of Exports from RoW	Intermediate Use of Domestic Product	Final Use by Country A of Exports from RoW	Final Use by Country B of Exports from RoW	Final Use of Domestic Product	Output from RoW
		Value Added	Value Added	Value Added				
		Total Output	Total Output	Total Output				

Figure 11: Data used (highlighted in blue) for open global model analysis.

Moving from an open model to a more closed model involves the consideration of final use and value added quantities, as shown in Figure 12. With a few exceptions, this model makes use of all of the available data. Changes in inventory and purchases abroad are not included, as they may sum to negative numbers and produce unusable results. Moreover, they account for only a very small fraction of total system throughput, and it is unclear where they could be accounted for elsewhere, were corrections to be made. Closed models that include government and private spending allow closer correlation between monetary value of products and the embodied energy of those products, suggesting energy-based valuation (Costanza, 1980; Costanza and Herendeen, 1984).

		Country A I1 I2 I3 I4	Country B I1 I2 I3 I4	Rest of World I1 I2 I3 I4	Country A Final Use	Country B Final Use	Rest of World Final Use	Total Output
Country A	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use of Domestic Product	Intermediate Use by Country B of Exports from A	Intermediate Use by RoW of Exports from B	Final Use of Domestic Product	Final Use by Country B of Exports from A	Final Use by RoW of Exports from B	Output from A
Country B	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use by Country A of Exports from B	Intermediate Use of Domestic Product	Intermediate Use by RoW of Exports from B	Final Use by Country A of Exports from B	Final Use of Domestic Product	Final Use by RoW of Exports from B	Output from B
Rest of World	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use by Country A of Exports from RoW	Intermediate Use by Country B of Exports from RoW	Intermediate Use of Domestic Product	Final Use by Country A of Exports from RoW	Final Use by Country B of Exports from RoW	Final Use of Domestic Product	Output from RoW
		Value Added	Value Added	Value Added				
		Total Output	Total Output	Total Output				

Figure 12: Data used (highlighted in blue) for closed global model analysis.

Figure 13 shows the data used for the global input-output model. All data are used in this model, but only intermediate flows are considered endogenous. Added value flows are condensed into one node per industry per country and incorporated as exogenous inputs. Final use values are similarly considered as exogenous outputs. Inputs and outputs are incorporated into complexity metrics through equation 13.

		Country A I1 I2 I3 I4	Country B I1 I2 I3 I4	Rest of World I1 I2 I3 I4	Country A Final Use	Country B Final Use	Rest of World Final Use	Total Output
Country A	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use of Domestic Product	Intermediate Use by Country B of Exports from A	Intermediate Use by RoW of Exports from B	Final Use of Domestic Product	Final Use by Country B of Exports from A	Final Use by RoW of Exports from B	Output from A
Country B	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use by Country A of Exports from B	Intermediate Use of Domestic Product	Intermediate Use by RoW of Exports from B	Final Use by Country A of Exports from B	Final Use of Domestic Product	Final Use by RoW of Exports from B	Output from B
Rest of World	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use by Country A of Exports from RoW	Intermediate Use by Country B of Exports from RoW	Intermediate Use of Domestic Product	Final Use by Country A of Exports from RoW	Final Use by Country B of Exports from RoW	Final Use of Domestic Product	Output from RoW
		Value Added	Value Added	Value Added				
		Total Output	Total Output	Total Output				

Figure 13: Data used for global input-output model analysis. Intermediate flows are highlighted in blue. Data included as exogenous inputs and outputs are in green and yellow, respectively.

Figure 14 shows the WIOT data used for the open domestic model. In this model, only national intermediate use values are selected and used. Each country is considered individually, instead of being aggregated into a set of global metrics. The data represent only the monetary value of outputs from the industries of a country used as inputs to industries from the same country.

		Country A I1 I2 I3 I4	Country B I1 I2 I3 I4	Rest of World I1 I2 I3 I4	Country A Final Use	Country B Final Use	Rest of World Final Use	Total Output
Country A	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use of Domestic Product	Intermediate Use by Country B of Exports from A	Intermediate Use by RoW of Exports from B	Final Use of Domestic Product	Final Use by Country B of Exports from A	Final Use by RoW of Exports from B	Output from A
Country B	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use by Country A of Exports from B	Intermediate Use of Domestic Product	Intermediate Use by RoW of Exports from B	Final Use by Country A of Exports from B	Final Use of Domestic Product	Final Use by RoW of Exports from B	Output from B
Rest of World	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use by Country A of Exports from RoW	Intermediate Use by Country B of Exports from RoW	Intermediate Use of Domestic Product	Final Use by Country A of Exports from RoW	Final Use by Country B of Exports from RoW	Final Use of Domestic Product	Output from RoW
		Value Added	Value Added	Value Added				
		Total Output	Total Output	Total Output				

Figure 14: Data used (highlighted in blue) for open domestic model analysis. Metrics are calculated for each country.

Figure 15 shows the data used for the closed domestic model analysis. Again, final use and value added data are included, but only within each country. Inventory change and purchases abroad data are once again excluded for the reasons described above. All use of domestic product is endogenous for the closed domestic model.

		Country A I1 I2 I3 I4	Country B I1 I2 I3 I4	Rest of World I1 I2 I3 I4	Country A Final Use	Country B Final Use	Rest of World Final Use	Total Output
Country A	**Industry 1** **Industry 2** **Industry 3** **Industry 4**	Intermediate Use of Domestic Product	Intermediate Use by Country B of Exports from A	Intermediate Use by RoW of Exports from B	Final Use of Domestic Product	Final Use by Country B of Exports from A	Final Use by RoW of Exports from B	Output from A
Country B	**Industry 1** **Industry 2** **Industry 3** **Industry 4**	Intermediate Use by Country A of Exports from B	Intermediate Use of Domestic Product	Intermediate Use by RoW of Exports from B	Final Use by Country A of Exports from B	Final Use of Domestic Product	Final Use by RoW of Exports from B	Output from B
Rest of World	**Industry 1** **Industry 2** **Industry 3** **Industry 4**	Intermediate Use by Country A of Exports from RoW	Intermediate Use by Country B of Exports from RoW	Intermediate Use of Domestic Product	Final Use by Country A of Exports from RoW	Final Use by Country B of Exports from RoW	Final Use of Domestic Product	Output from RoW
		Value Added	**Value Added**	**Value Added**				
		Total Output	**Total Output**	**Total Output**				

Figure 15: Data used (highlighted in blue) for closed domestic model analysis. Metrics are calculated for each country.

The domestic input-output model is shown in Figure 16. Added value flows are condensed into one node per industry per country and incorporated as exogenous inputs. Final use values are similarly considered as exogenous outputs. Additionally, intermediate use by other countries of products from the country of interest is included in the output value. Intermediate use of products from other countries is considered in the input. Thus, where the domestic open and closed models describe the economy of each country strictly based on domestic flows, the domestic input-output model is the same as the global input-output model, but broken down by country.

		Country A I1 I2 I3 I4	Country B I1 I2 I3 I4	Rest of World I1 I2 I3 I4	Country A Final Use	Country B Final Use	Rest of World Final Use	Total Output
Country A	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use of Domestic Product	Intermediate Use by Country B of Exports from A	Intermediate Use by RoW of Exports from B	Final Use of Domestic Product	Final Use by Country B of Exports from A	Final Use by RoW of Exports from B	Output from A
Country B	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use by Country A of Exports from B	Intermediate Use of Domestic Product	Intermediate Use by RoW of Exports from B	Final Use by Country A of Exports from B	Final Use of Domestic Product	Final Use by RoW of Exports from B	Output from B
Rest of World	Industry 1 Industry 2 Industry 3 Industry 4	Intermediate Use by Country A of Exports from RoW	Intermediate Use by Country B of Exports from RoW	Intermediate Use of Domestic Product	Final Use by Country A of Exports from RoW	Final Use by Country B of Exports from RoW	Final Use of Domestic Product	Output from RoW
		Value Added	Value Added	Value Added				
		Total Output	Total Output	Total Output				

Figure 16: Data used for domestic input-output model analysis. Intermediate flows are highlighted in blue. Data included as exogenous inputs and outputs are in green and yellow, respectively. Metrics are calculated for each country.

The MATLAB scripts used for this analysis accomplish the selection of the flows required for each model by looping through the entire WIOT and setting any flows that do not meet the selection criteria to zero. For instance, the open international trade model requires that no intermediate domestic, final use or value added flows are included. To exclude the final use and value added data, the initial import of the data is restricted to the intermediate use table cells. Since there are 35 industries represented in the WIOT per country, exclusion of the domestic is accomplished with a loop that selects the intersection of the first 35 columns and 35 rows, then the intersection of rows and columns 36 through 70, and so on. Once selected, these flows are set to zero.

Once the unnecessary flows are set to zero, another portion of the MATLAB script loops through each cell in the modified matrix and calculates the portion of each Ulanowicz metric contributed by that particular cell, using equations 9 through 12. Values of zero are ignored, since the logarithm of zero is undefined. In this way, the previously excluded values are not used in the calculations, since they have been set to zero. A running sum of the calculated values is kept in memory, which yields the final Ulanowicz metrics once the entire matrix has been looped through.

The final metrics are then written out to a text file for plotting, interpretation, and further calculations.

Additional calculations, including those for relative entropy, number of roles, and effective connectivity, are carried out in R, a statistical programming language. In addition, R scripts were used in the creation of plots for comparison of complexity metrics to energy data.

Chapter Three: Results

Time Series Results

Ulanowicz metrics were plotted by year for each model. Figure 17 shows times series plots of weighted metrics C, ϕ, and A, for both open and closed global models. A steady increase in value can be seen for all metrics between 2002 and 2008. A decrease is apparent between 2008 and 2009, with values increasing after that. The results for the open model are lower than those for the closed model. Results for the global input-output model are between those for the open and closed models, but much closer to those for the open model. For the weighted metrics, the differences between models are largely explained by differences in total system throughput. Throughput is significantly higher for the closed model.

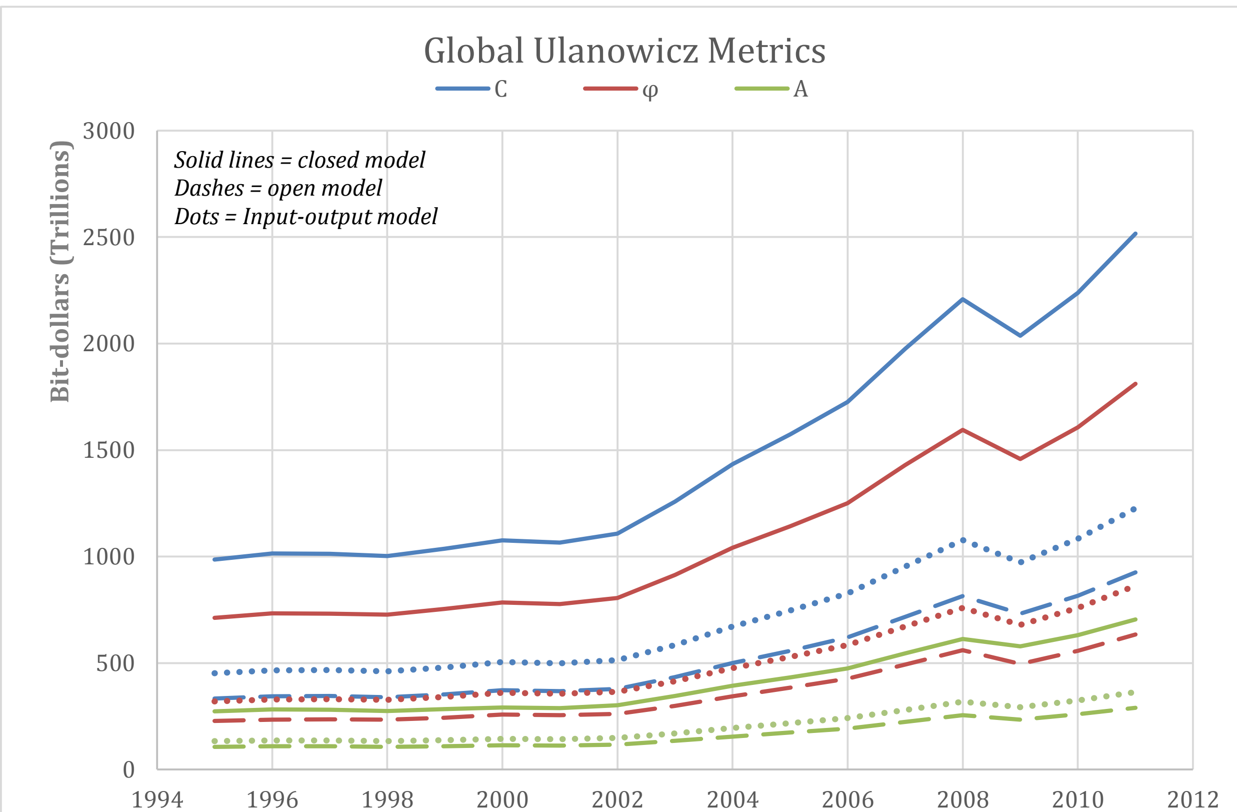


Figure 17: Time series of weighted Ulanowicz metrics for open, closed, and input-output global models.

Time series plots of the un-weighted Ulanowicz metrics, H, ψ and X, shown in Figure 18, indicate a rather different trend. The values change very little over the entire time period covered by the WIOD, with the exception of slight decreases between 2008 and 2009 evident for H and ψ. Unlike the weighted results, the open model results are larger than the closed model results. The input-output metrics are consistently the lowest. This is likely due to the relatively high system throughput and comparatively small system.

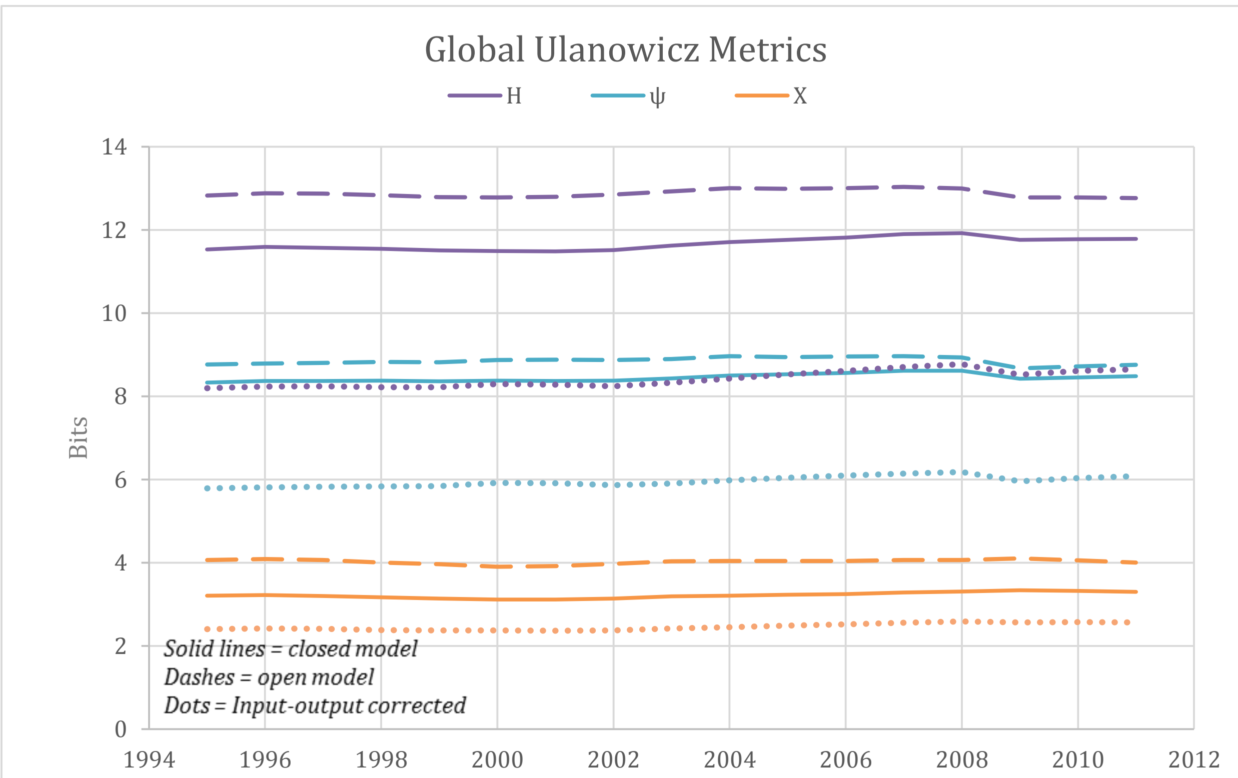


Figure 18: Time series of un-weighted Ulanowicz metrics for open, closed, and input-output global models.

Figures 19 through 36 show the weighted Ulanowicz metrics in time series for open, closed, and input-output domestic models. The United States, China, Japan, and rest of the world consistently have the highest weighted metrics among the non European Union countries for both closed and open models. With the exception of Japan, the metrics for those countries are generally increasing from 1995 to 2001. Germany, Italy, France, Spain, and the United Kingdom have the highest values among the European Union countries. For all countries, open model values are lower than closed model values. The sequence of countries from high metric values to low metric values is generally preserved, regardless of the metric or model. The relationship between China and the United States is a notable and recurring exception; for each metric, the open and input-output model values for China surpass those of the United States toward the end of the time series. In the closed model, The United States metrics are the highest for the entire time series. The point where the Chinese metrics overtake those for the United States typically occurs later for the input-output model than it does for the open model.

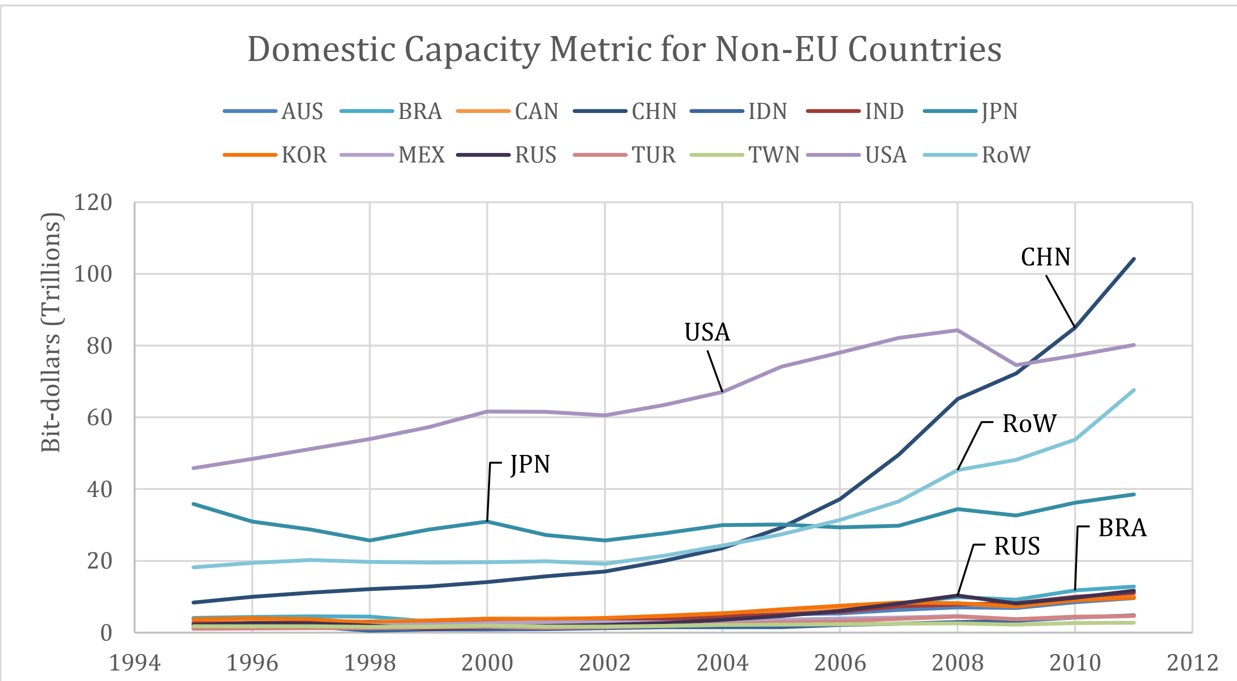


Figure 19: Open model domestic capacity (C) time series for non European Union countries

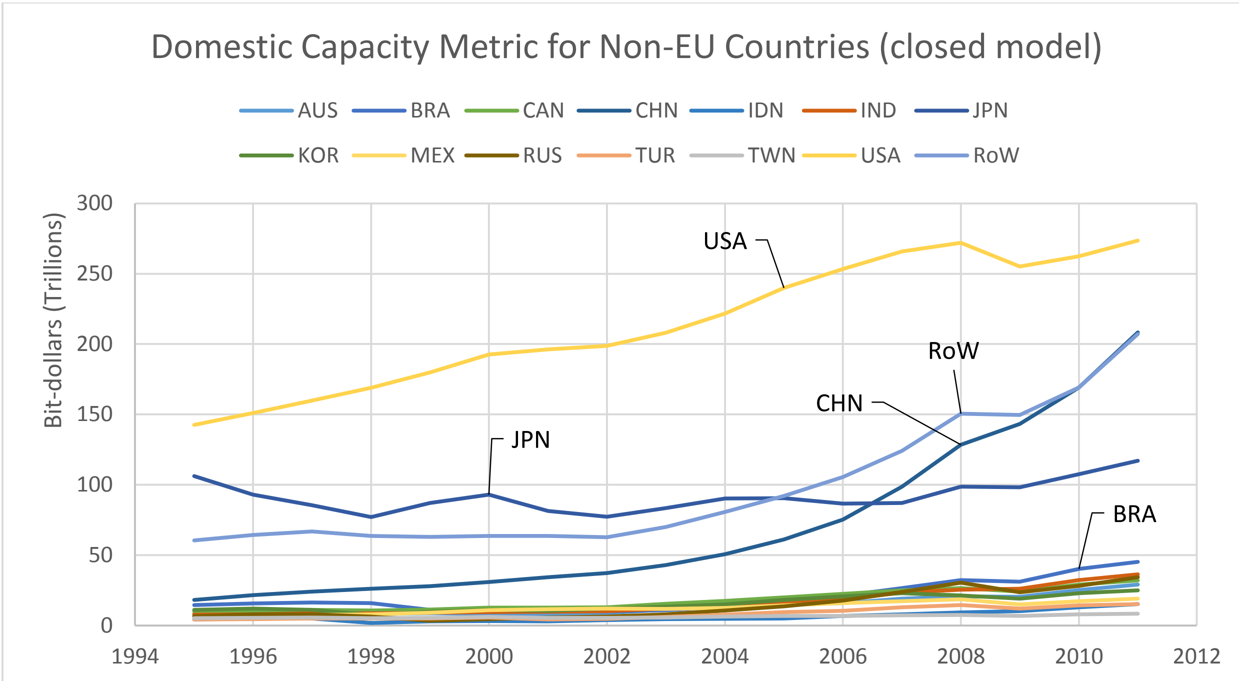


Figure 20: Closed model domestic capacity (C) time series for non European Union countries

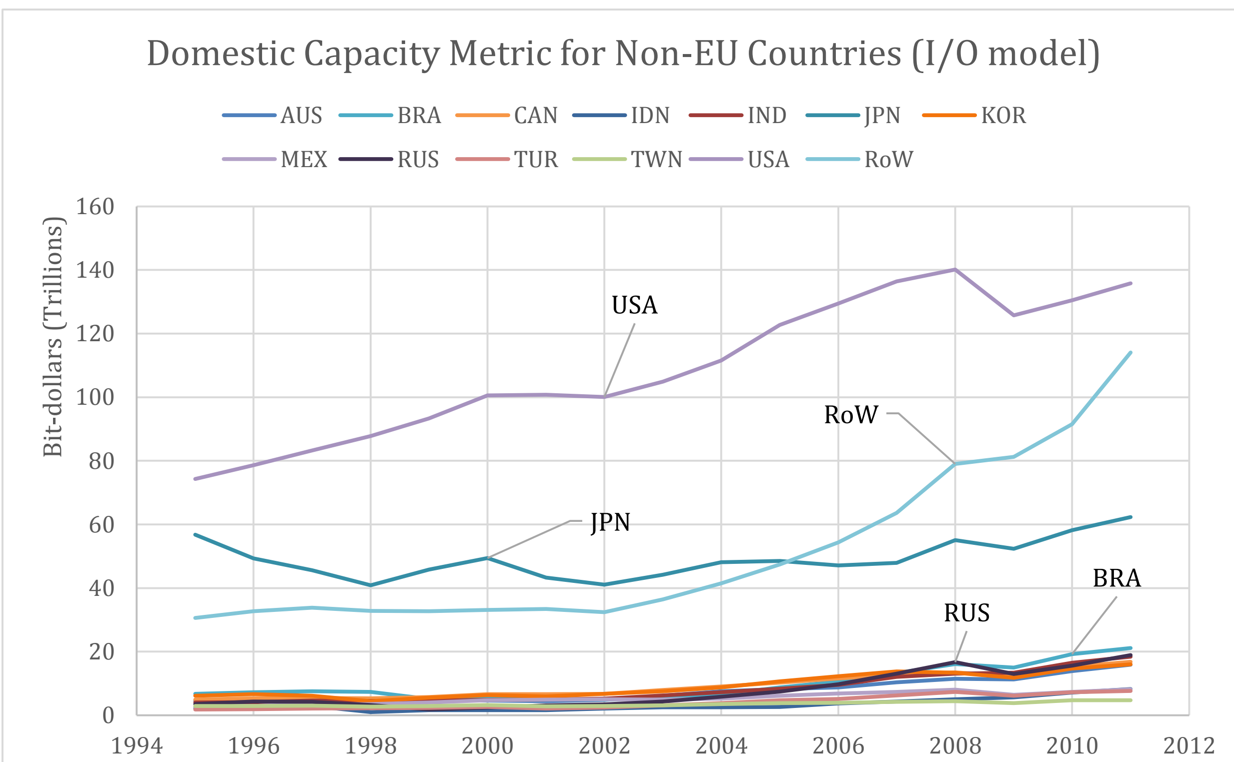


Figure 21: Input-output model domestic capacity (C) time series for non European Union countries

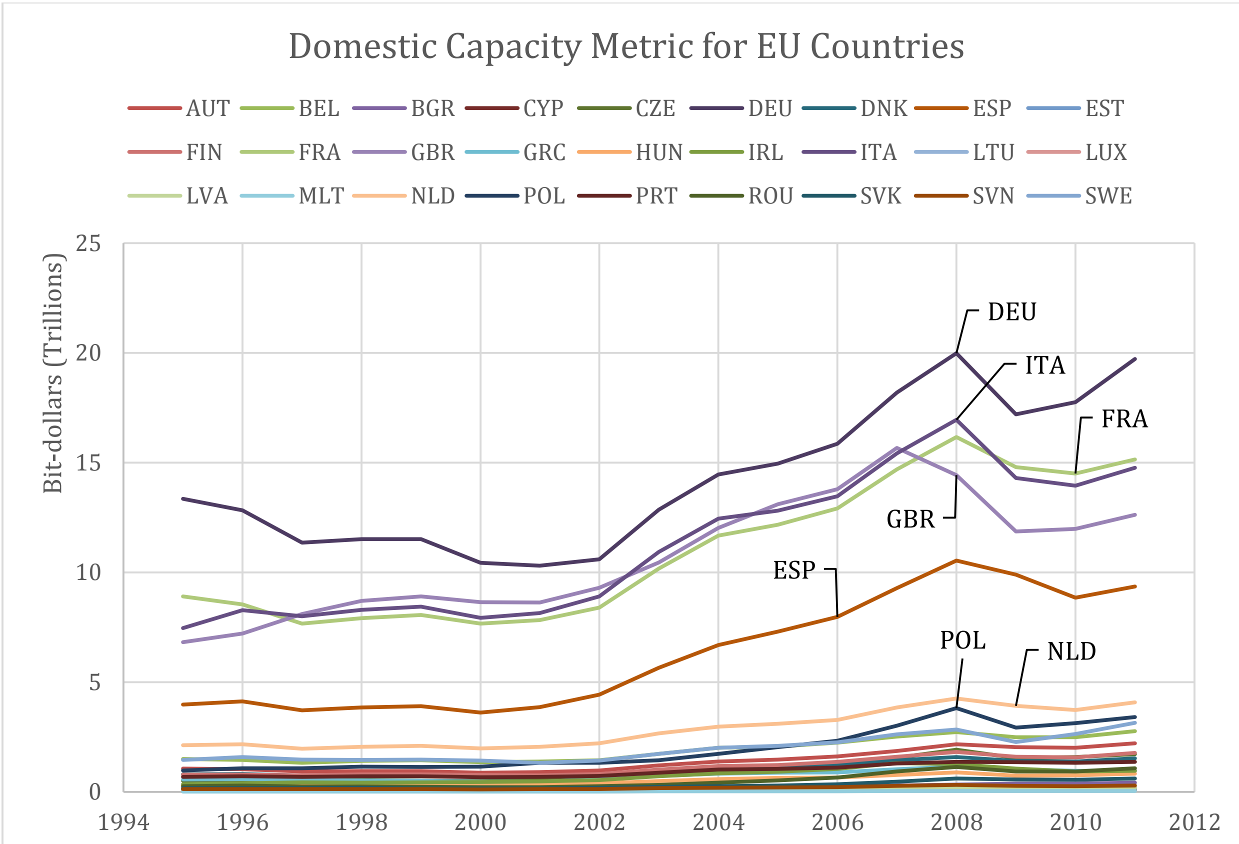


Figure 22: Open model domestic capacity (C) time series for European Union countries

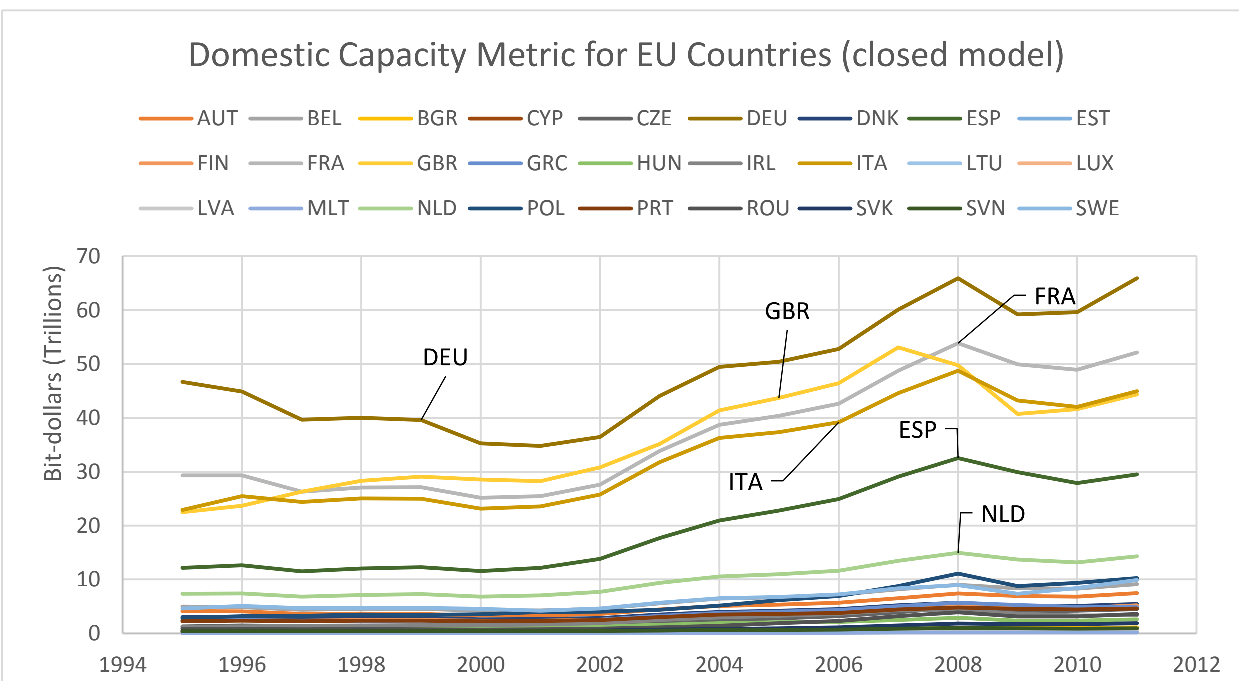


Figure 23: Closed model domestic capacity (C) time series for European Union countries

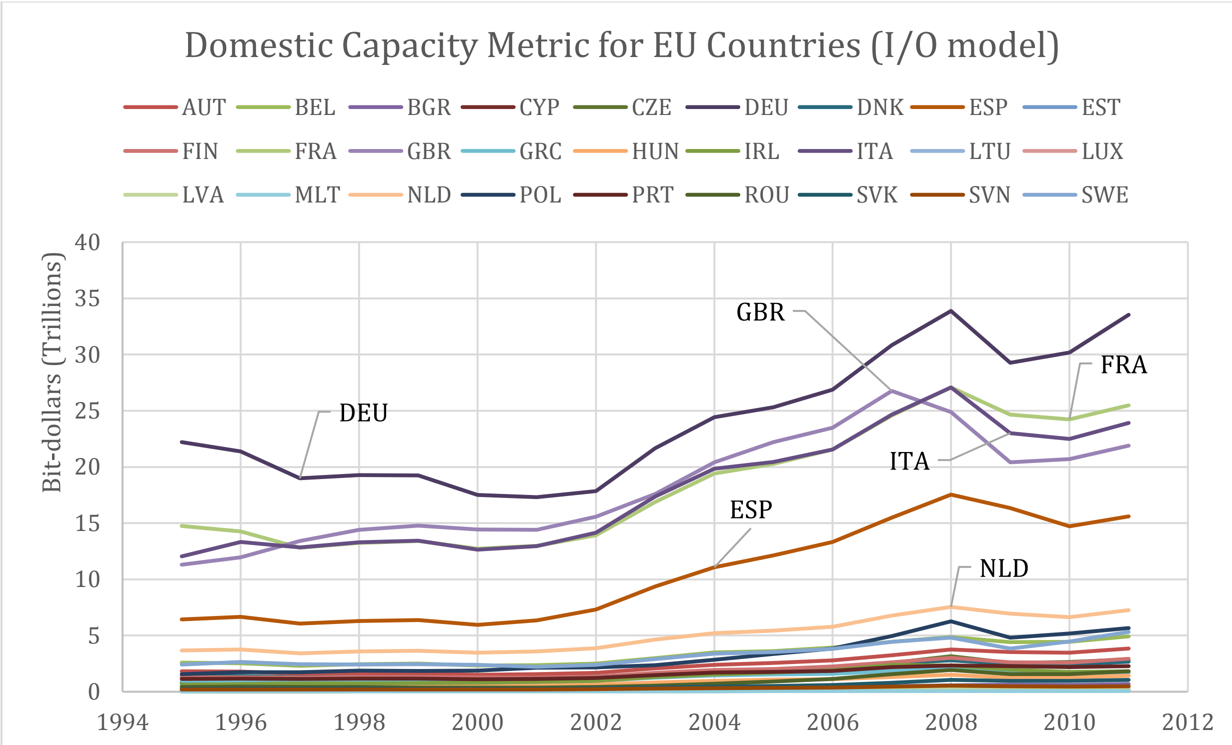


Figure 24: Input-output model domestic capacity (C) time series for European Union countries

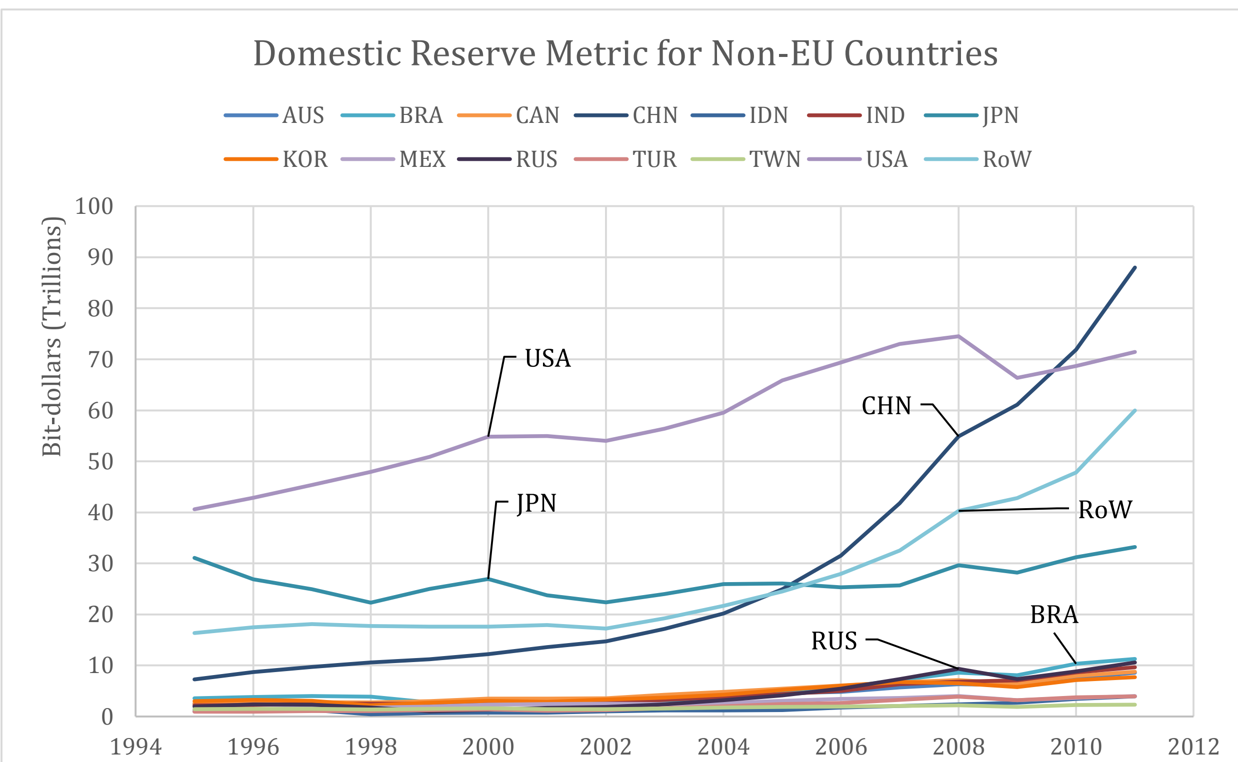


Figure 25: Open model domestic reserve (ϕ) time series for non European Union countries

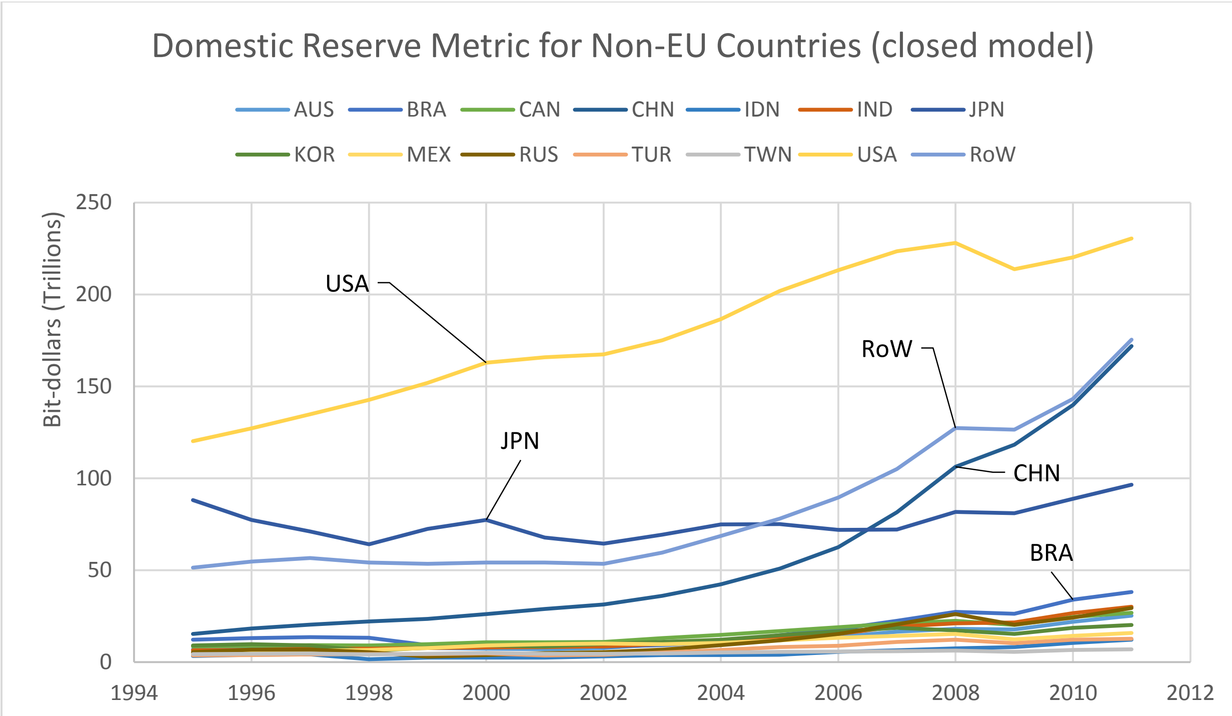


Figure 26: Closed model domestic reserve (ϕ) time series for non European Union countries

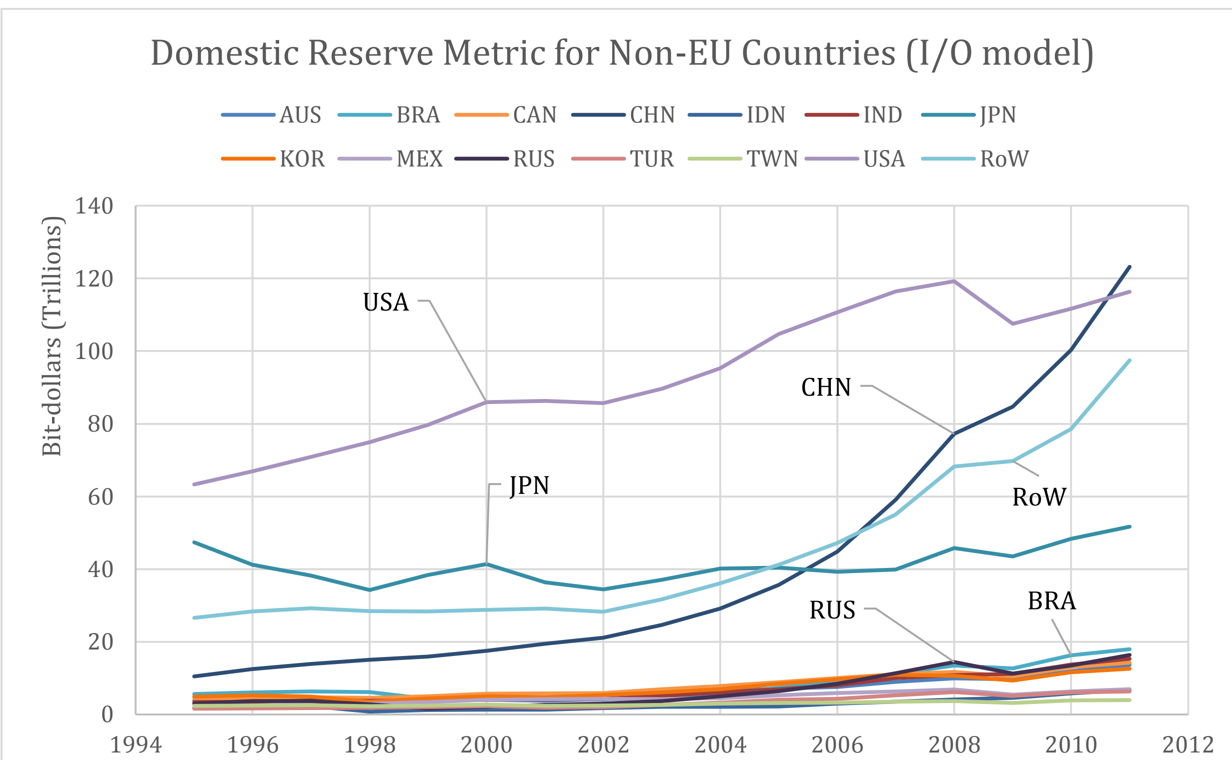


Figure 27: Input-output model domestic reserve (ϕ) time series for non European Union countries

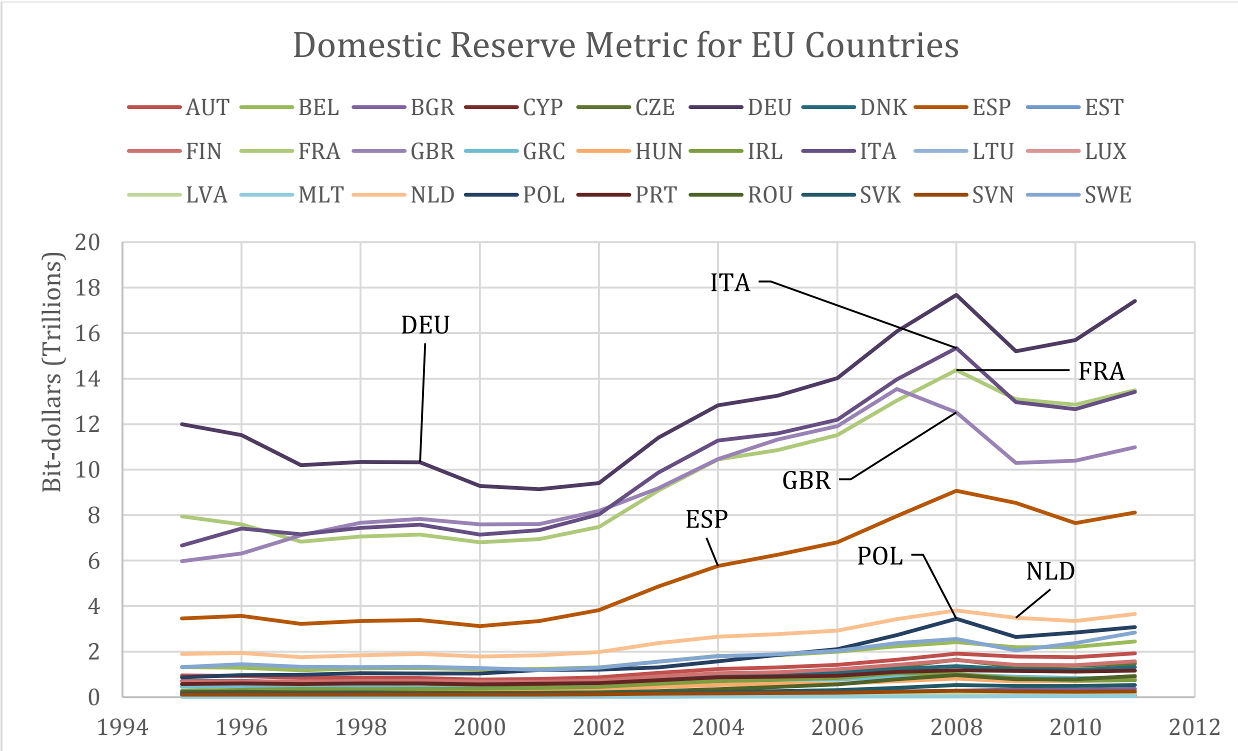


Figure 28: Open model domestic reserve (ϕ) time series for European Union countries

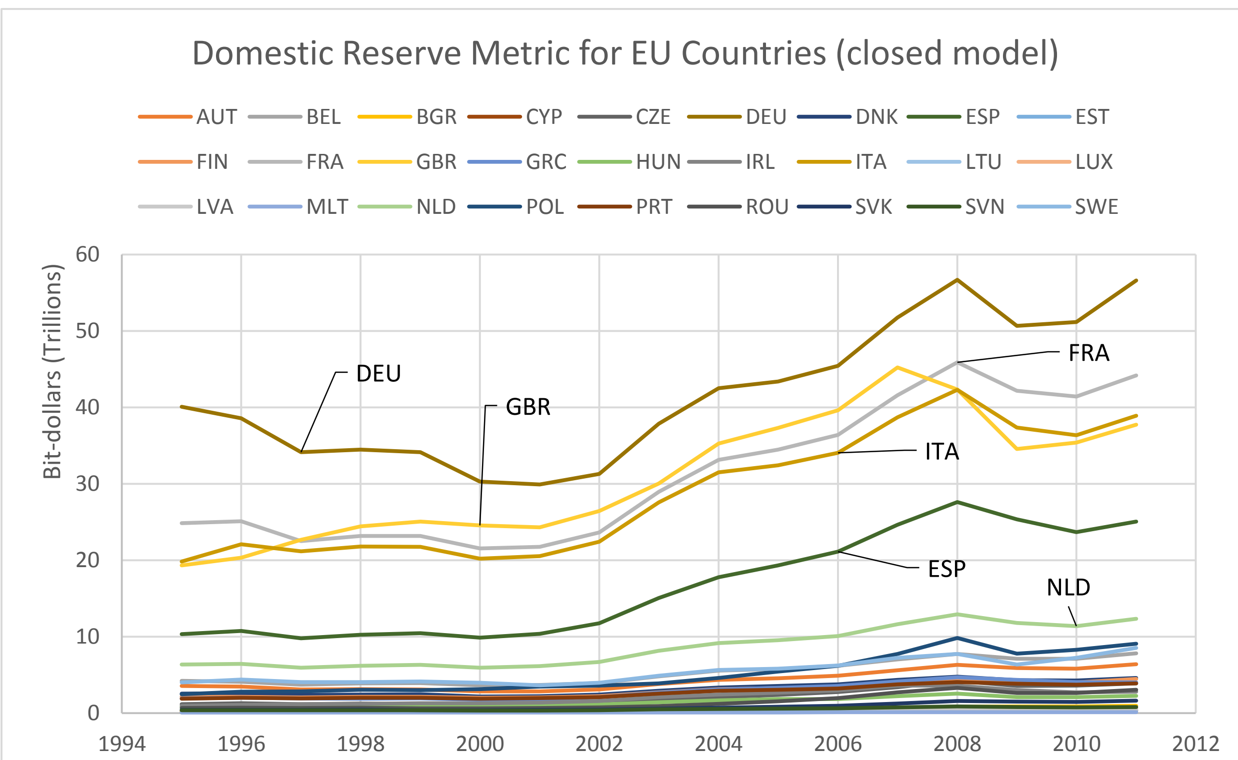


Figure 29: Closed model domestic reserve (ϕ) time series for European Union countries

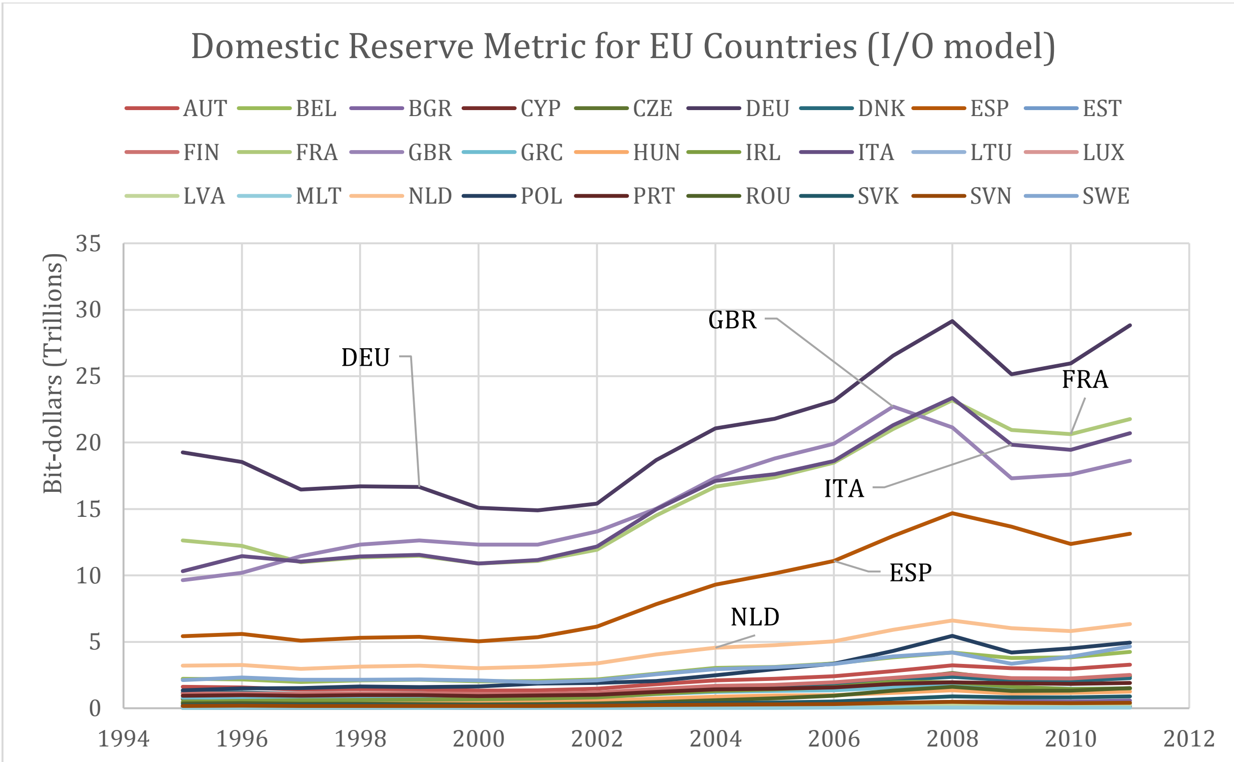


Figure 30: Input-output model domestic reserve (ϕ) time series for European Union countries

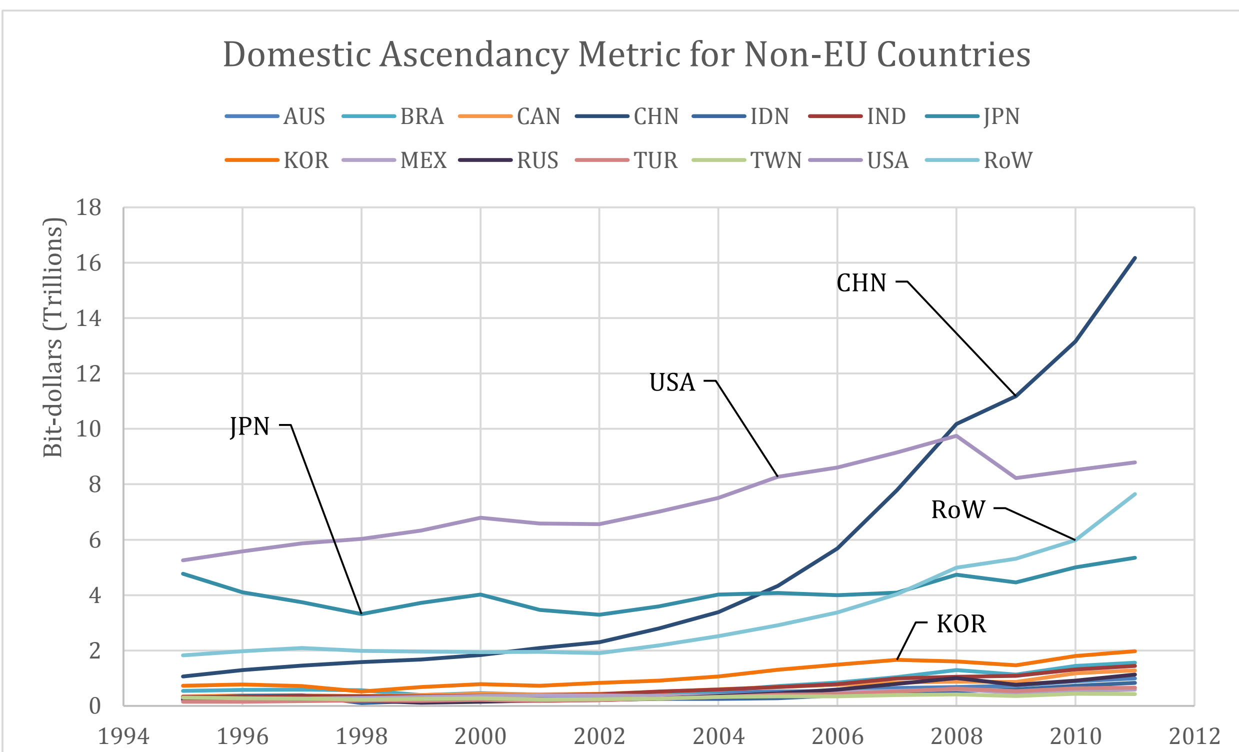


Figure 31: Open model domestic ascendancy (A) time series for non European Union countries

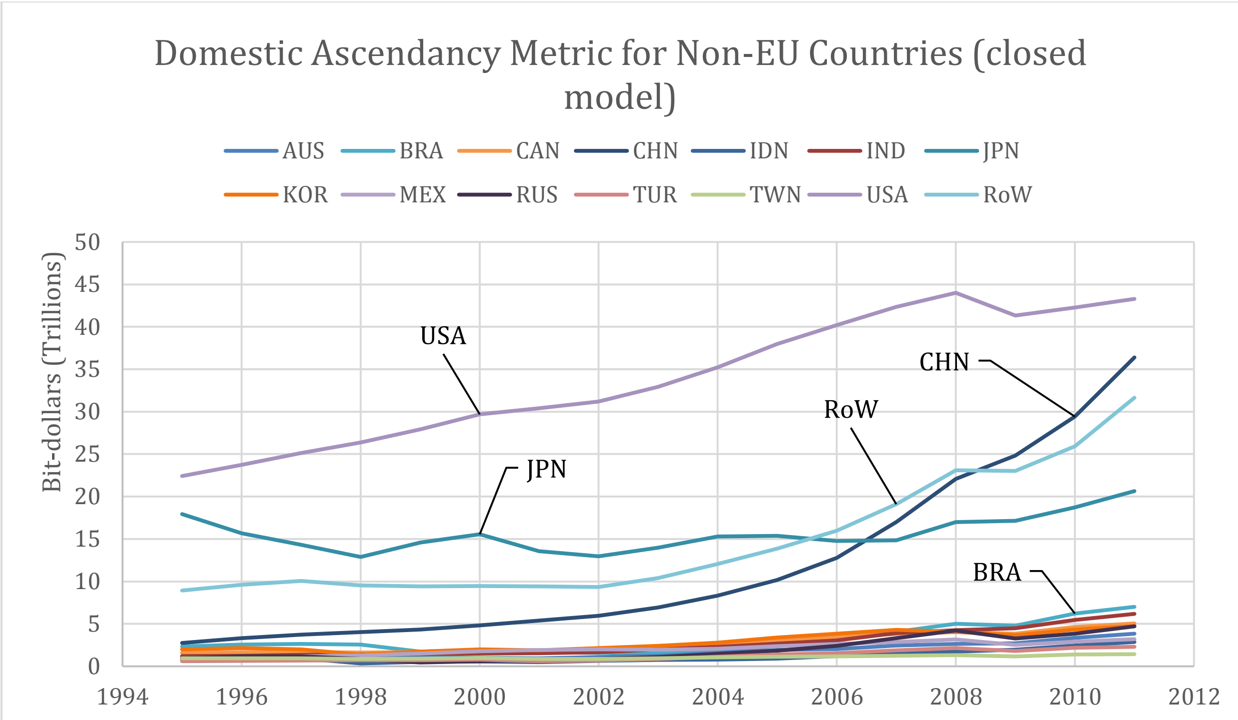


Figure 32: Closed model domestic ascendancy (A) time series for non European Union countries

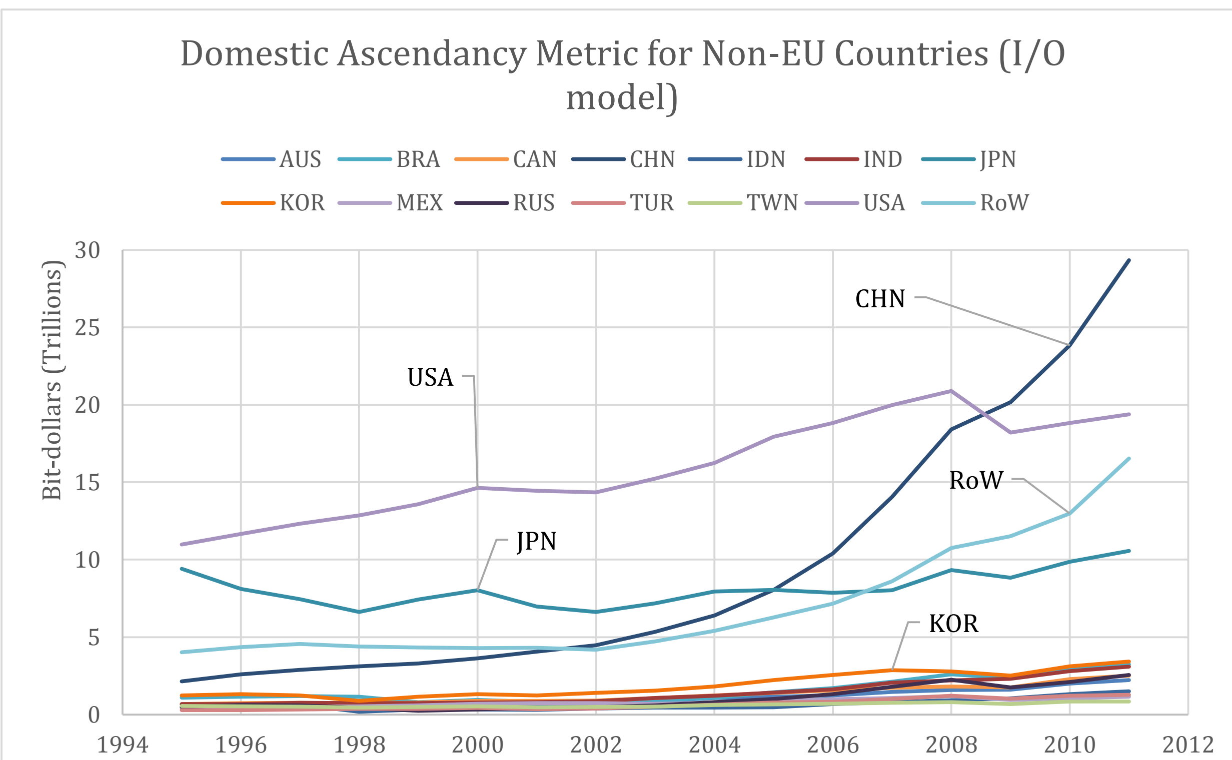


Figure 33: Input-output model domestic ascendancy (A) time series for non European Union countries

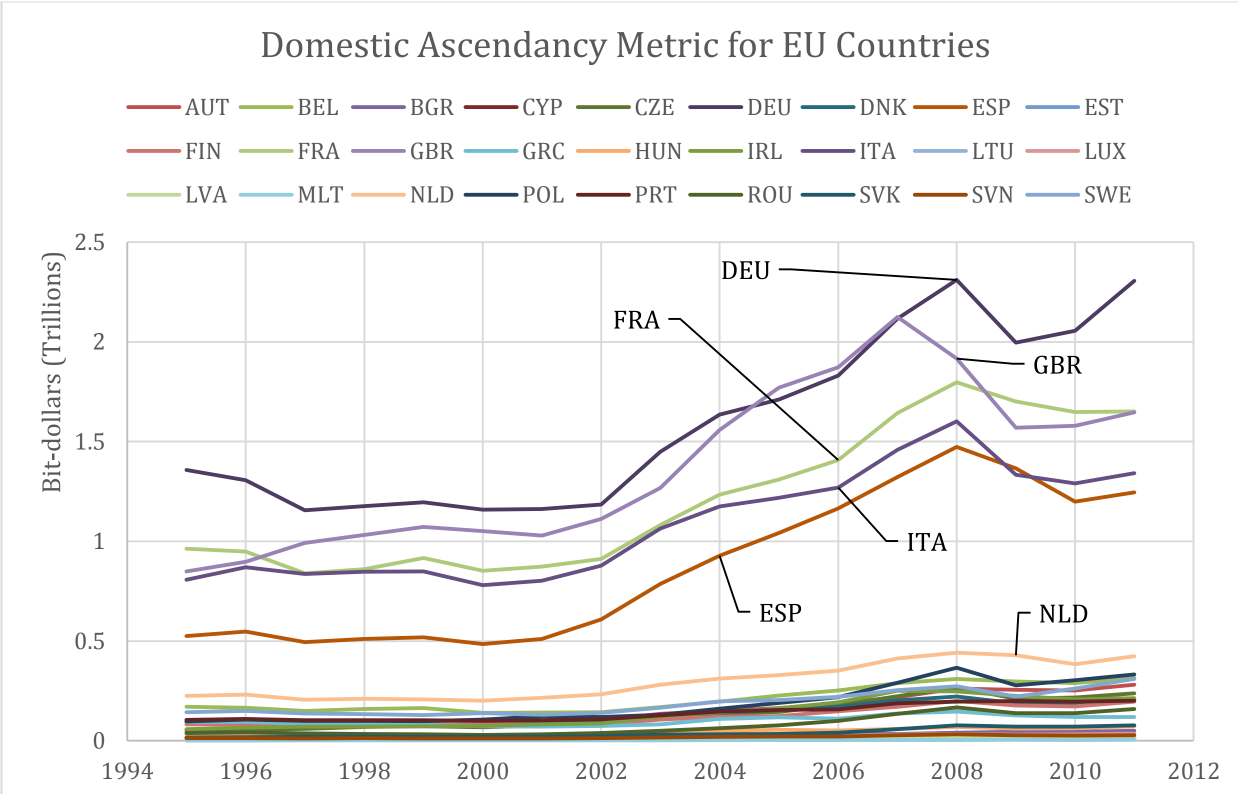


Figure 34: Open model domestic ascendancy (A) time series for European Union countries

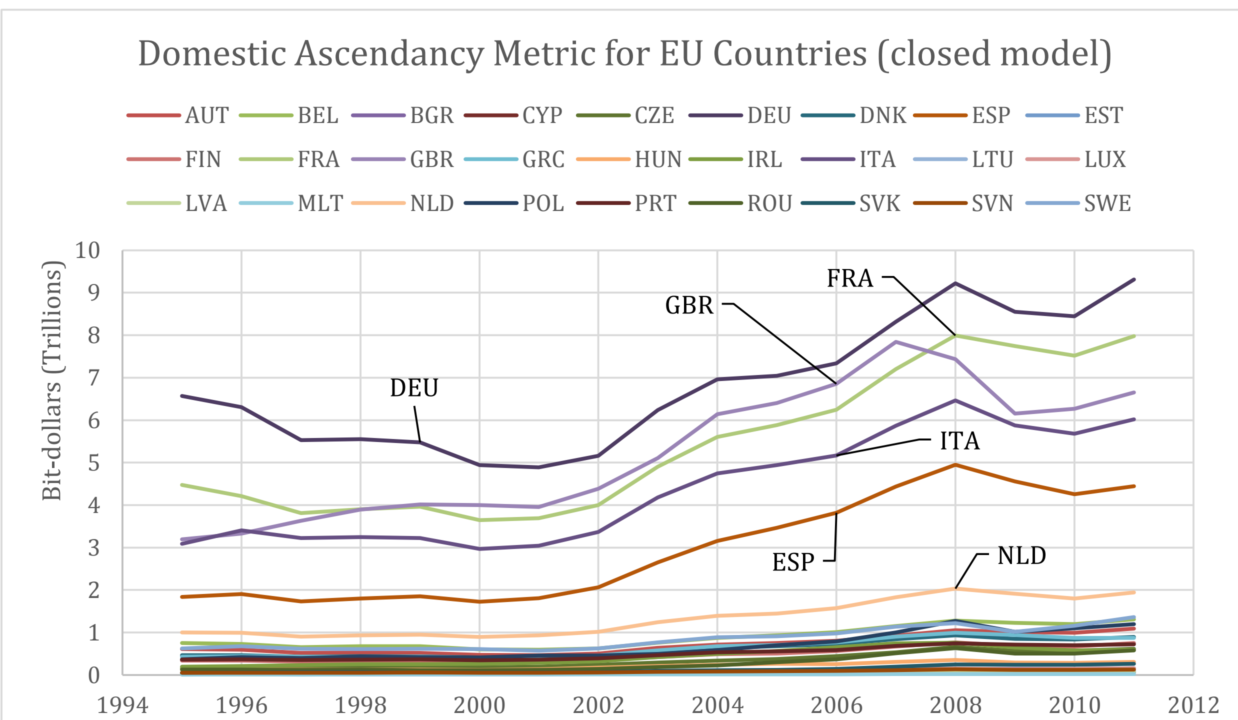


Figure 35: Closed model domestic ascendancy (A) time series for European Union countries

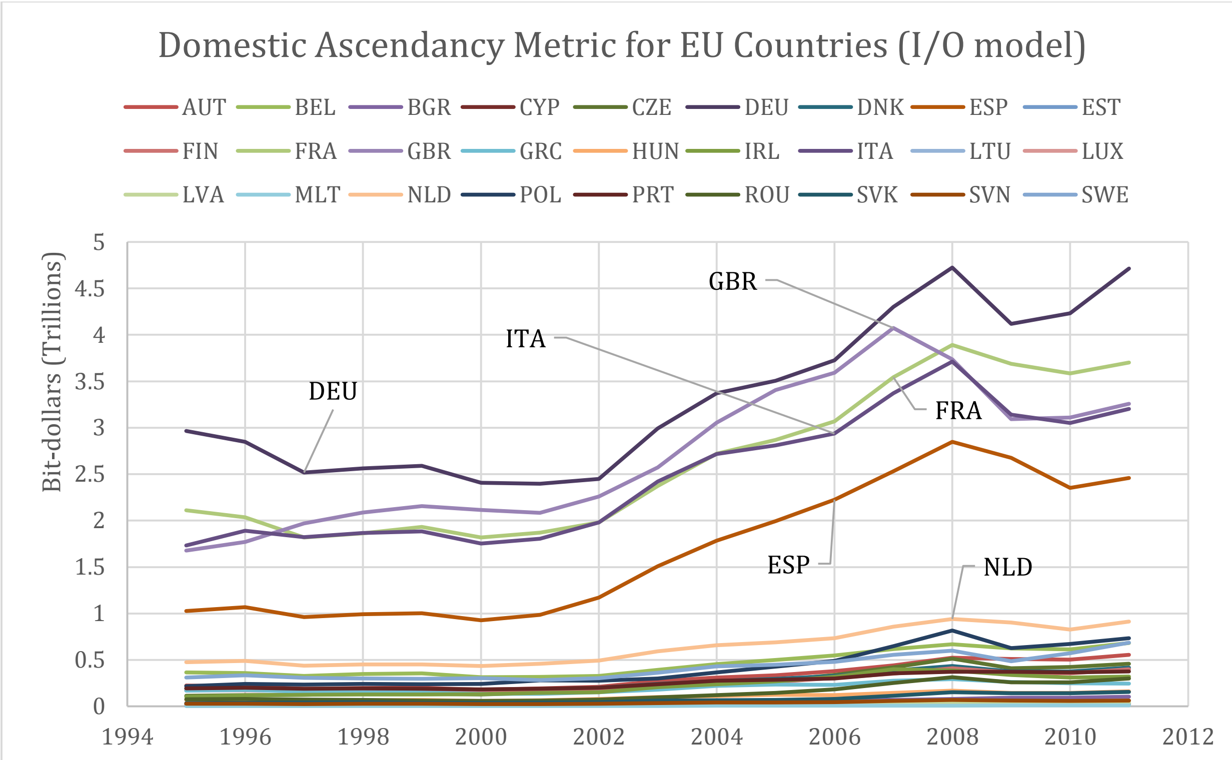


Figure 36: Input-output model domestic ascendancy (A) time series for European Union countries

Figures 37 through 56 show the un-weighted Ulanowicz metrics in time series for open and closed domestic models. Few clear and consistent trends are observable. Metrics for Luxembourg tend to be significantly lower than those for other European Union countries, and decreasing between 1995 and 2007. Cyprus, Greece, Ireland, and Malta typically have lower aggregate indeterminacy and conditional entropy values than all countries but Luxembourg. These same countries generally have relatively high mutual constraint values, compared to other European Union countries, but this is not consistent for the three models.

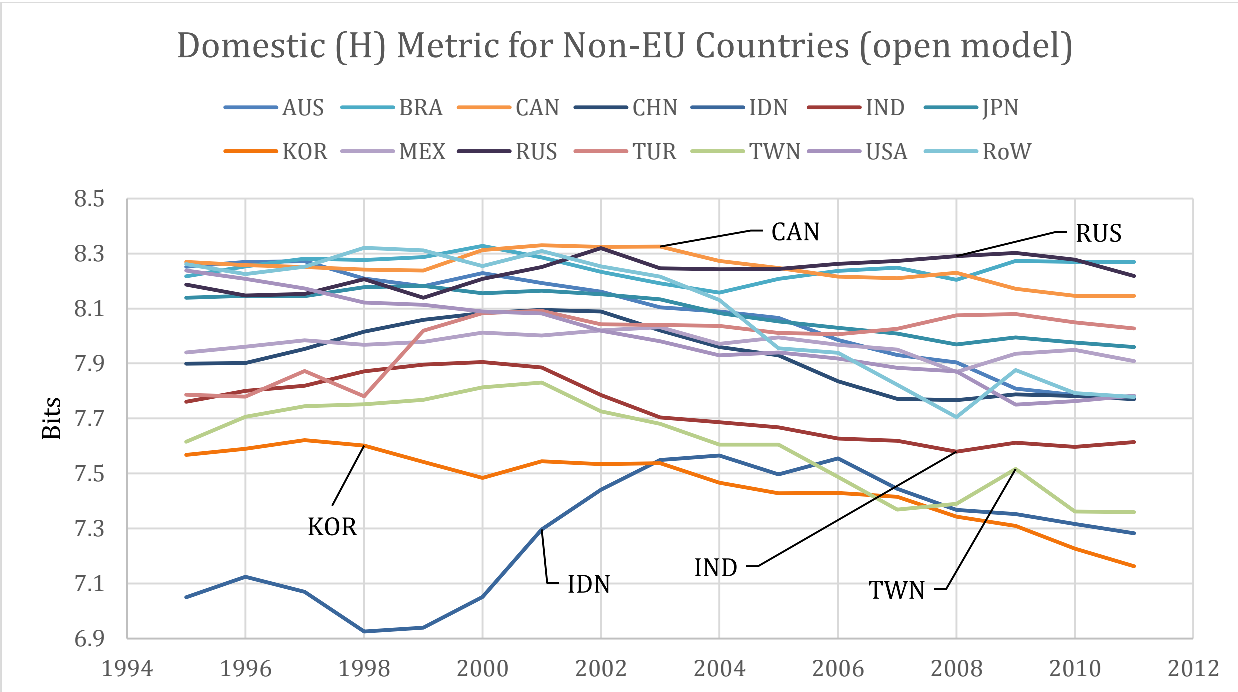


Figure 37: Open model aggregate indeterminacy (H) time series for non European Union countries

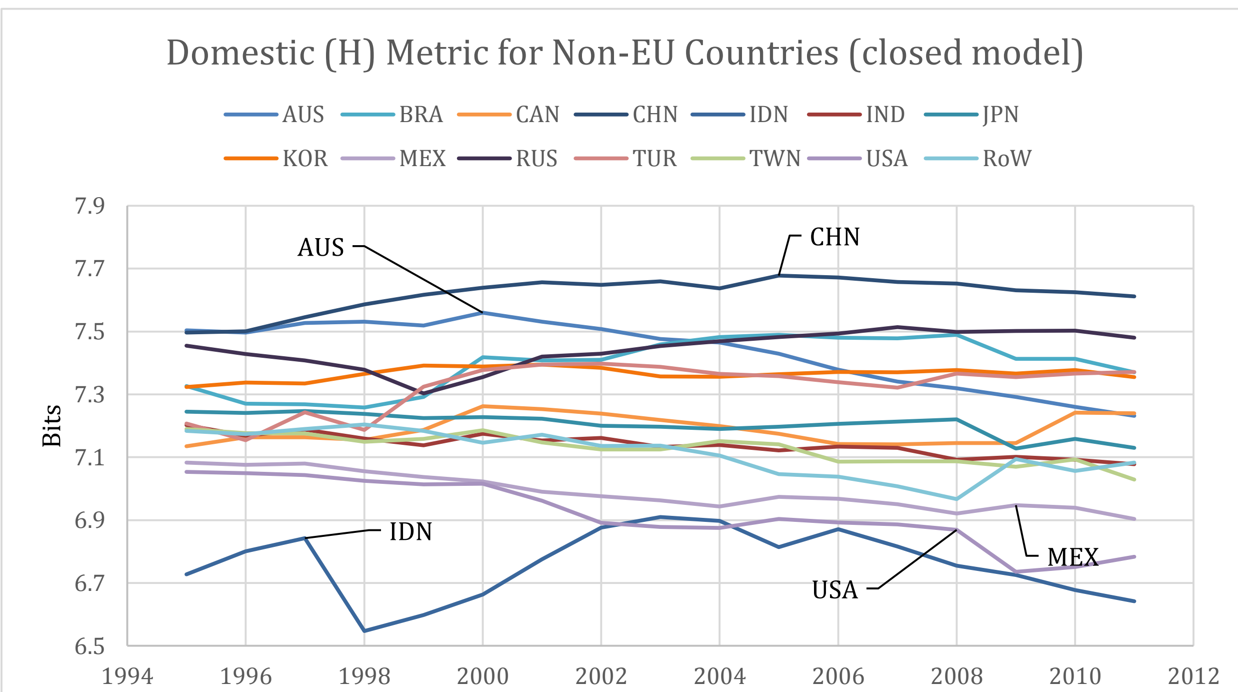


Figure 38: Closed model aggregate indeterminacy (H) time series for non European Union countries

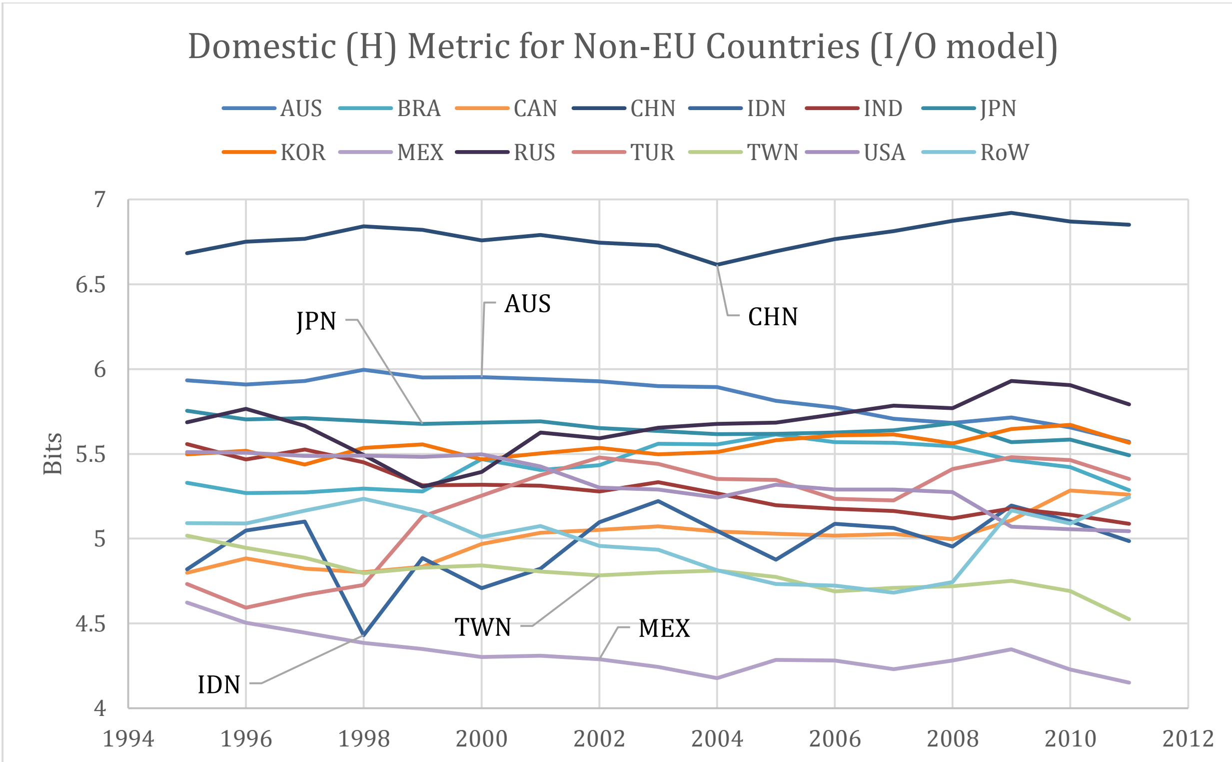


Figure 39: Input-output model aggregate indeterminacy (H) time series for non European Union countries

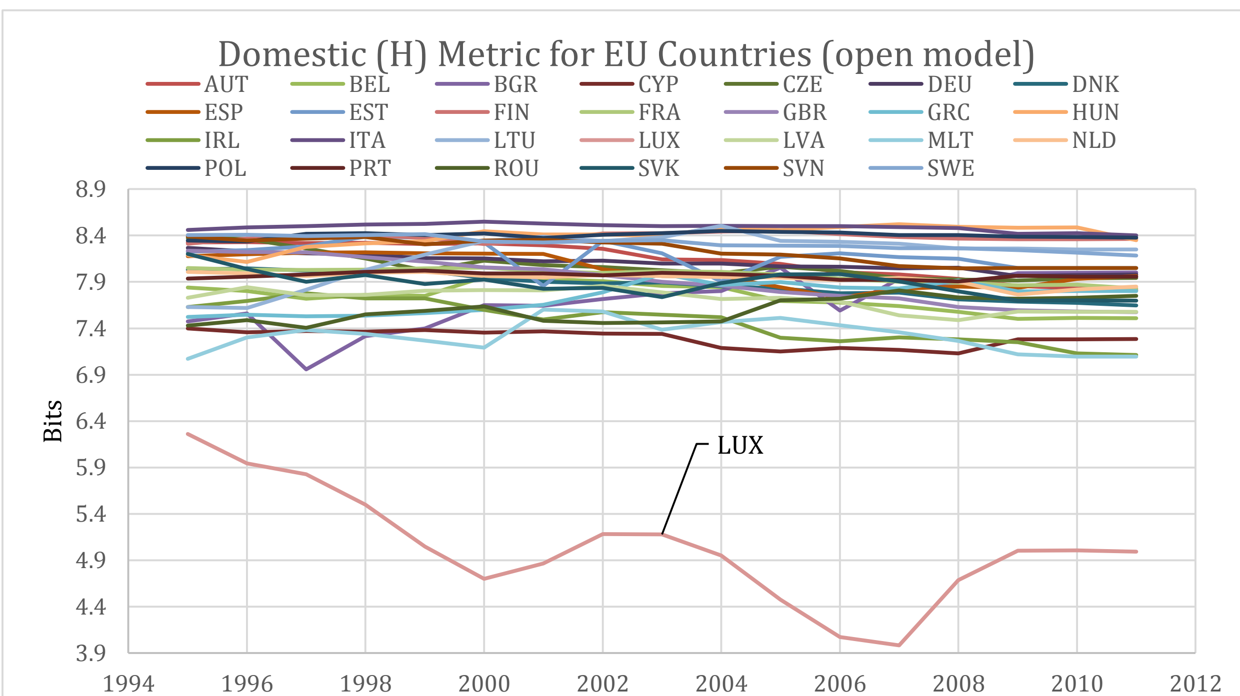


Figure 40: Open model aggregate indeterminacy (H) time series for European Union countries

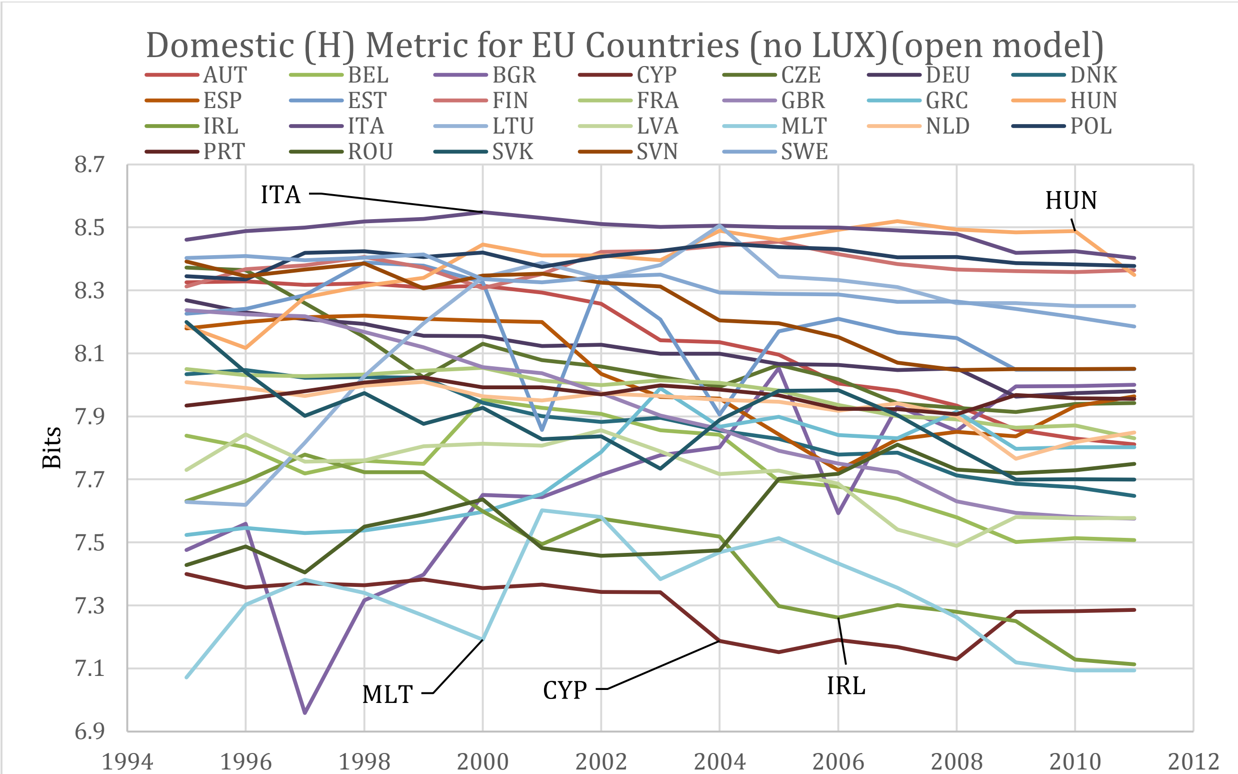


Figure 41: Open model aggregate indeterminacy (H) time series for non European Union countries, excluding Luxembourg

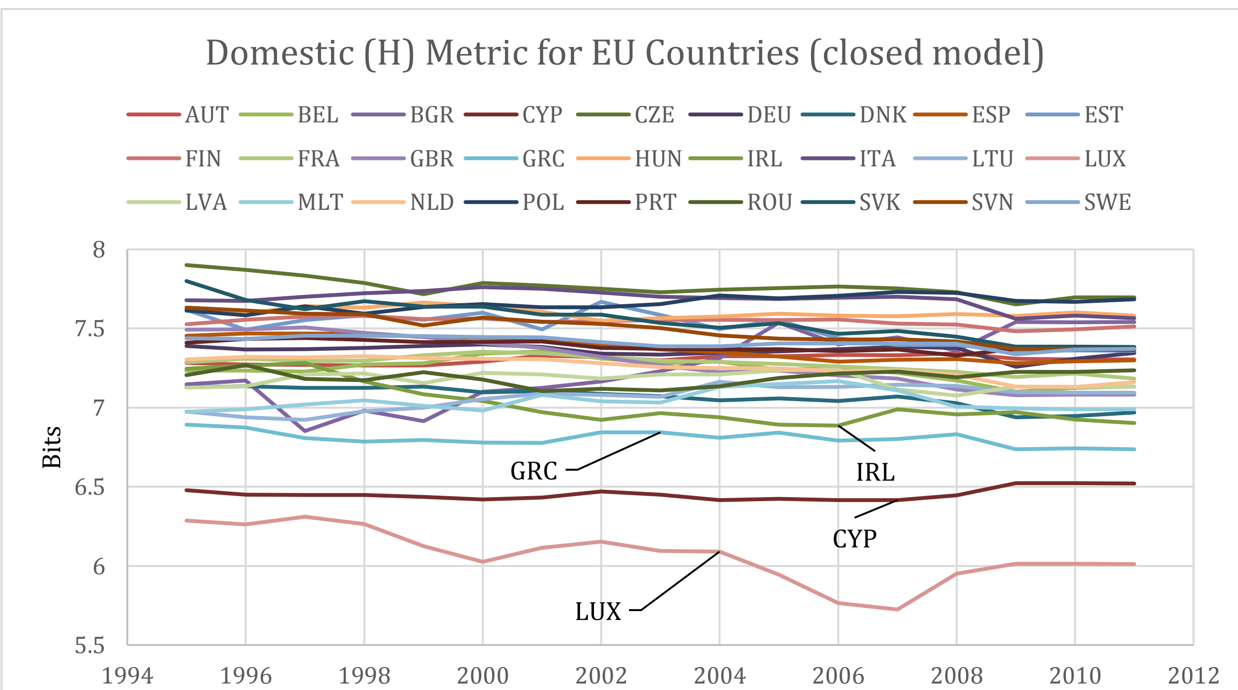


Figure 42: Closed model aggregate indeterminacy (H) time series for European Union countries

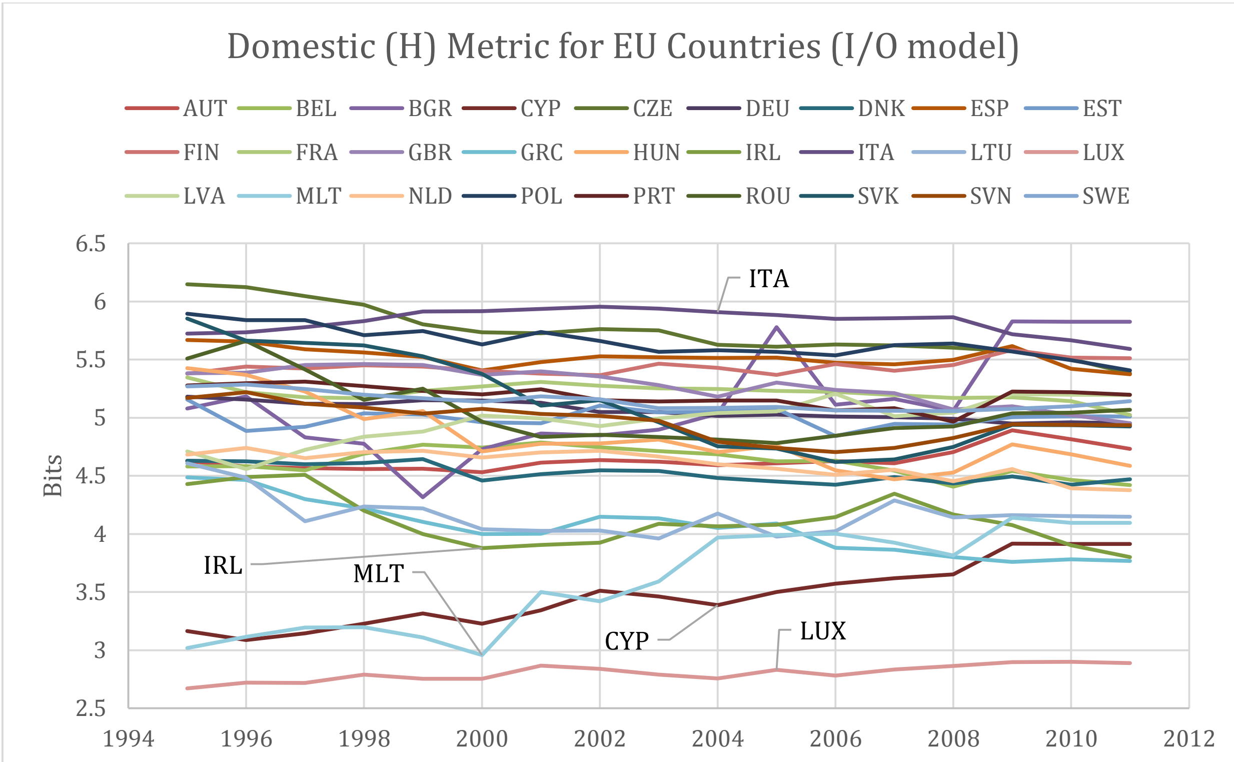


Figure 43: Input-output model aggregate indeterminacy (H) time series for European Union countries

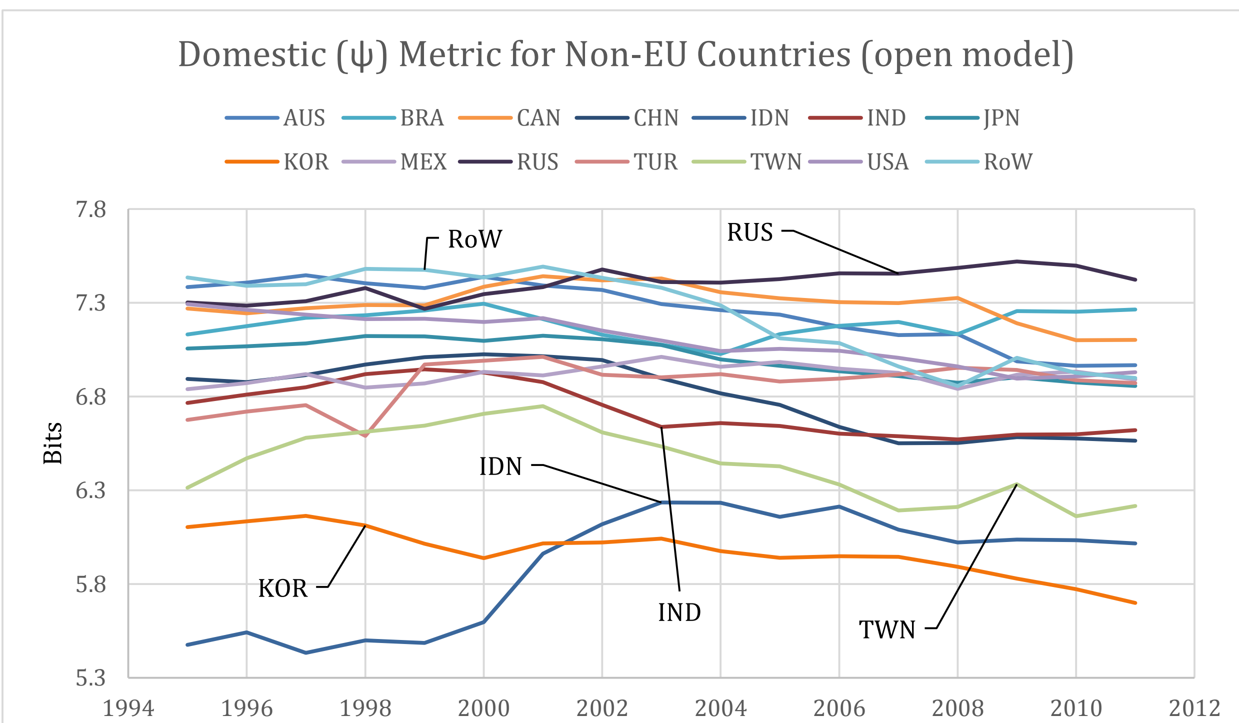


Figure 44: Open model conditional entropy (ψ) time series for non European Union countries

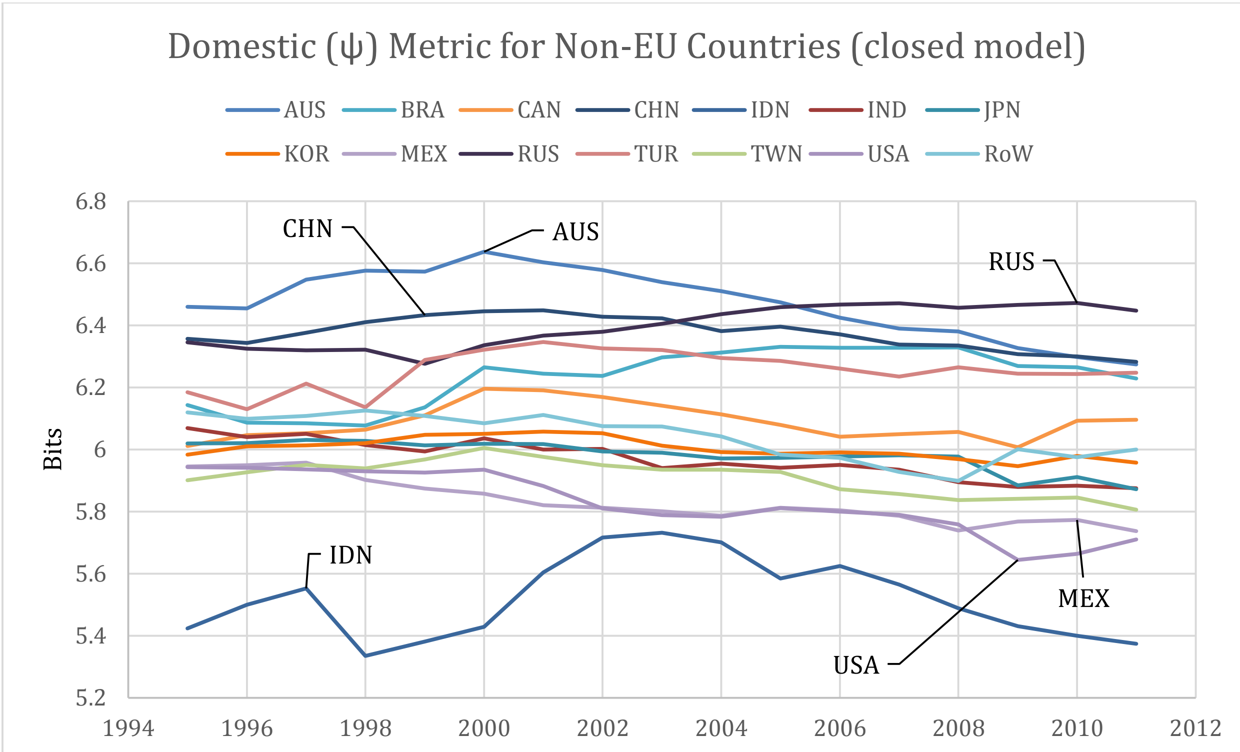


Figure 45: Closed model conditional entropy (ψ) time series for non European Union countries

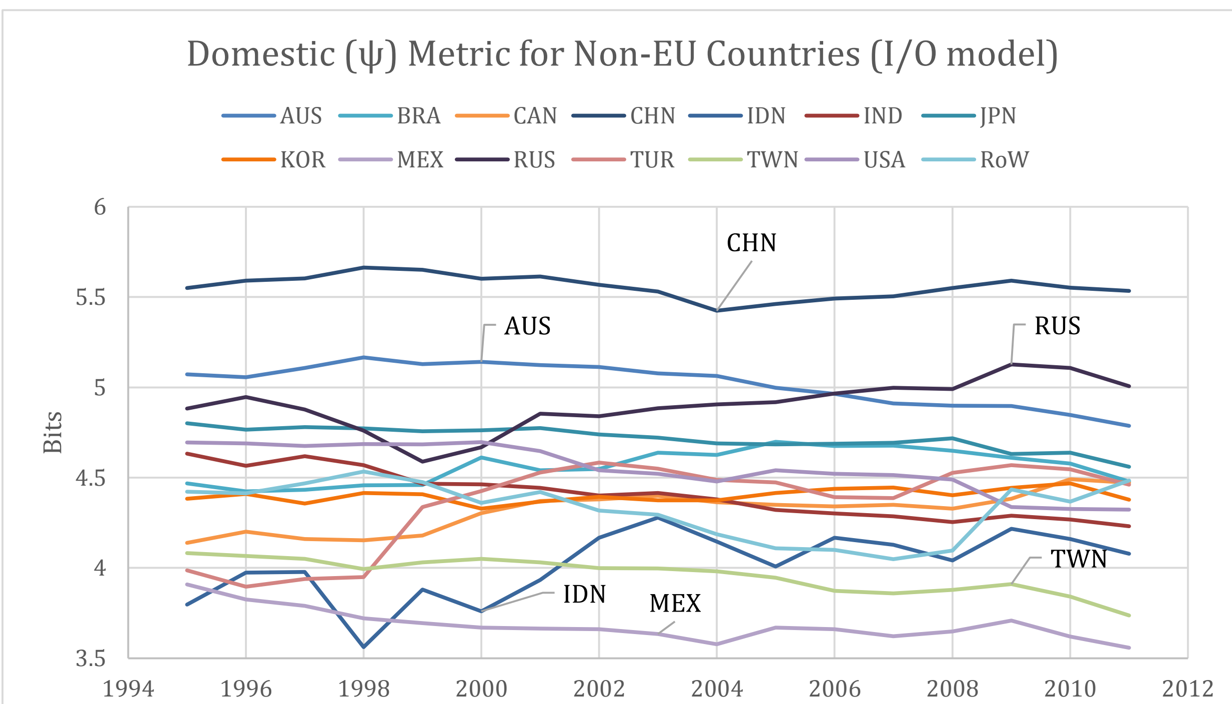


Figure 46: Input-output model conditional entropy (ψ) time series for non European Union countries

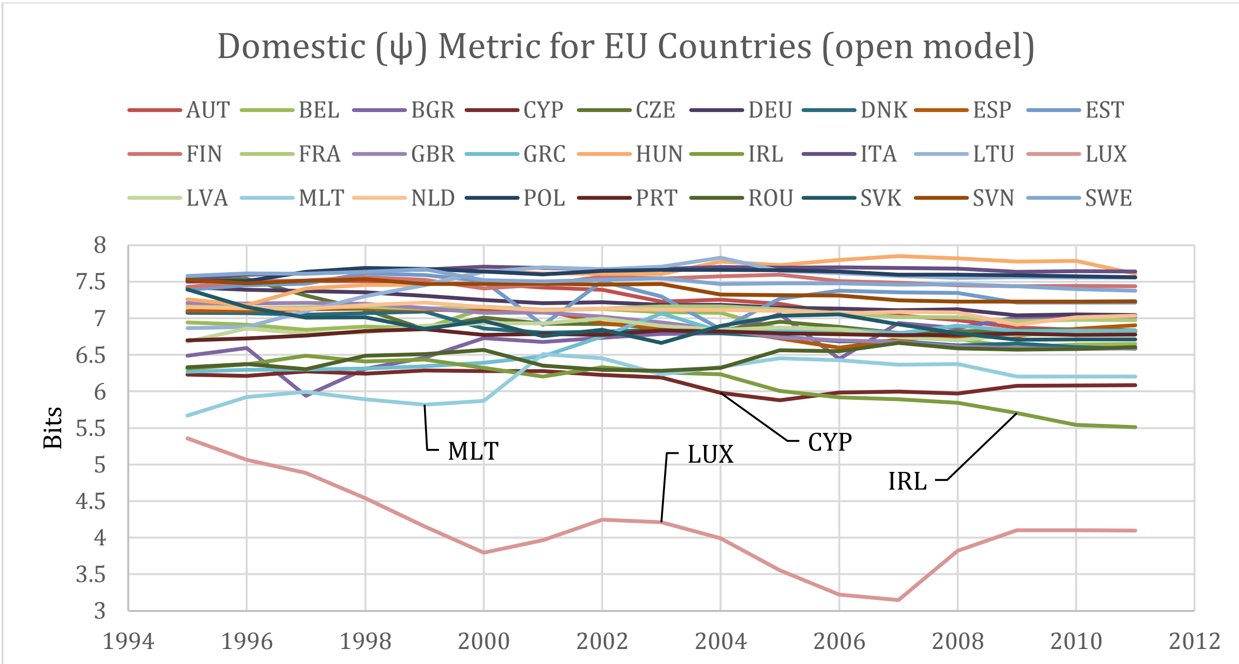


Figure 47: Open model conditional entropy (ψ) time series for European Union countries

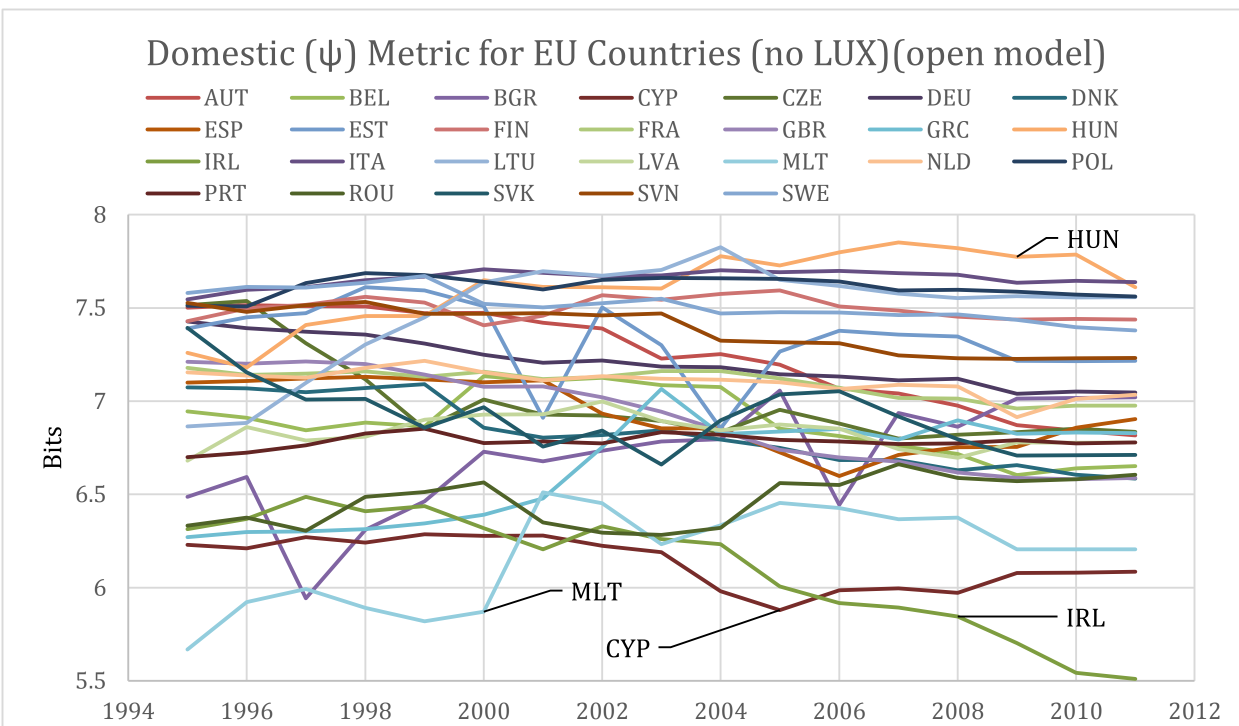


Figure 48: Open model conditional entropy (ψ) time series for European Union countries, excluding Luxembourg

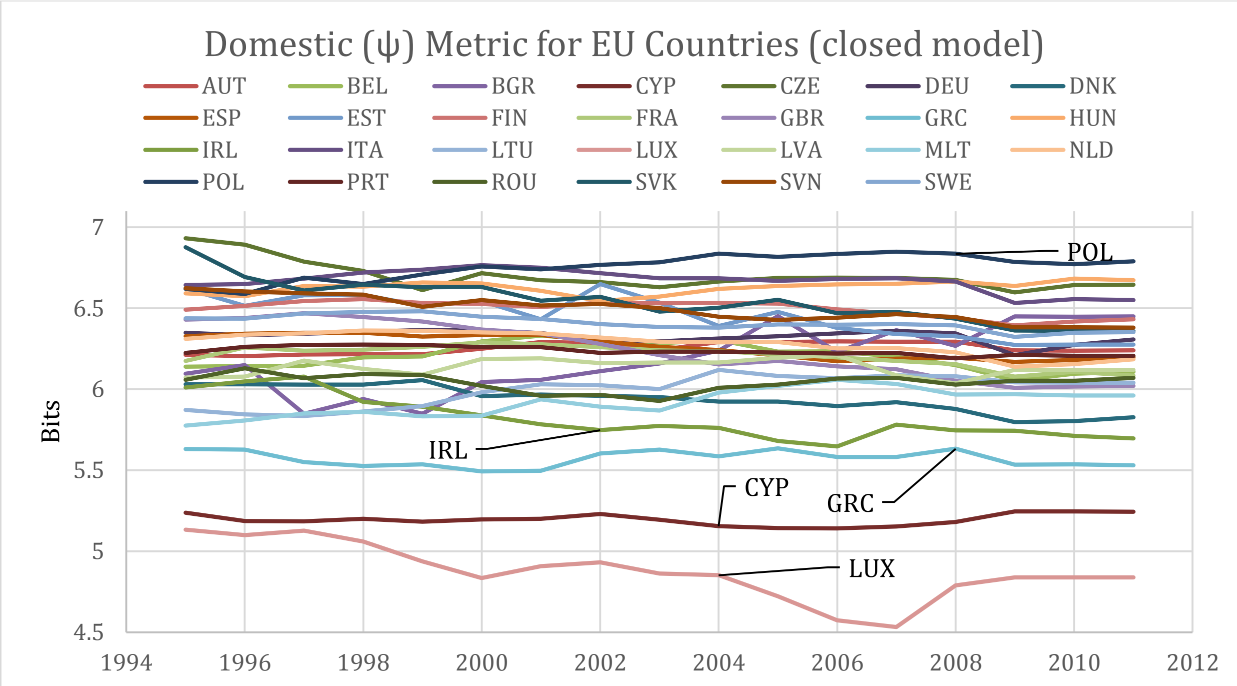


Figure 49: Closed model conditional entropy (ψ) time series for European Union countries

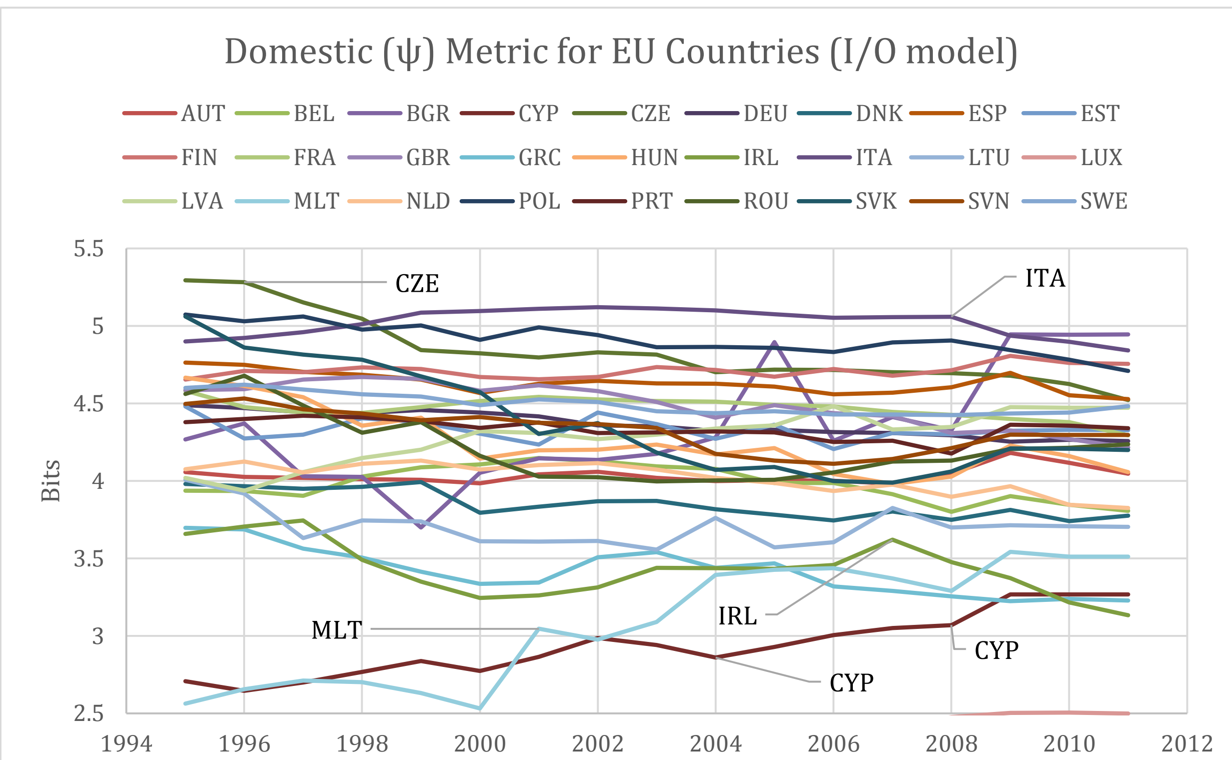


Figure 50: Input-output model conditional entropy (ψ) time series for European Union countries

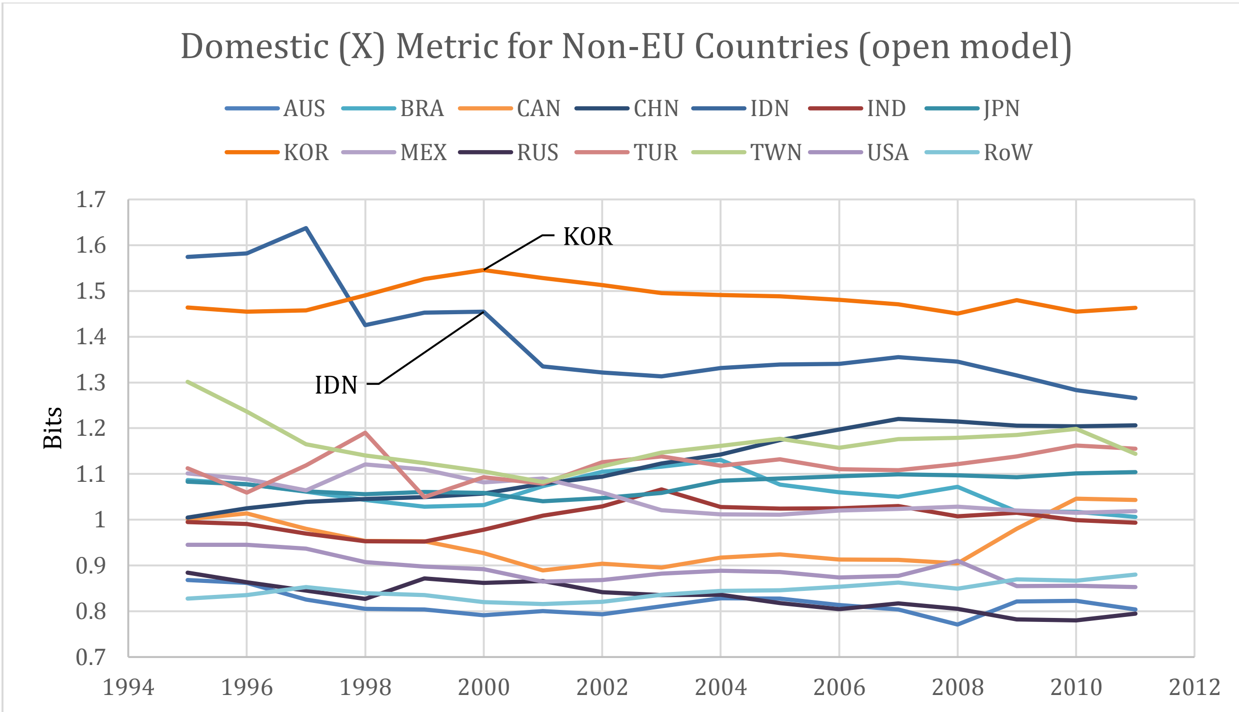


Figure 51: Open model average mutual constraint (X) time series for non European Union countries

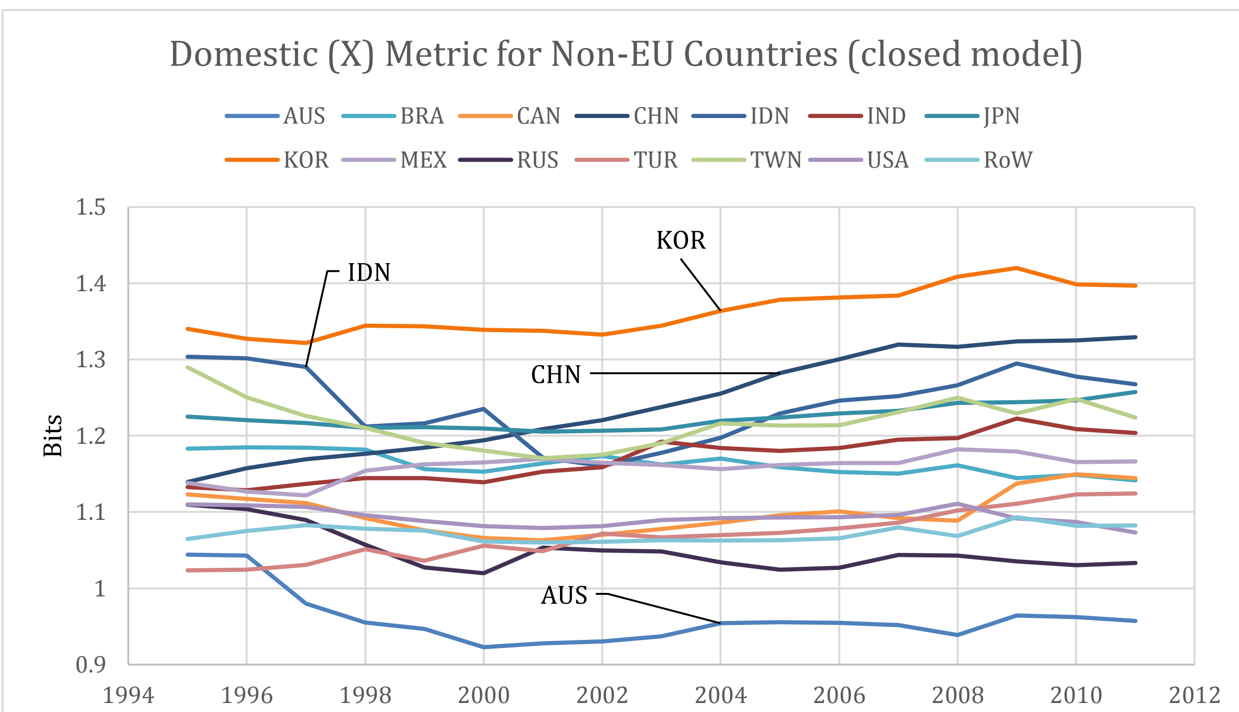


Figure 52: Closed model average mutual constraint (X) time series for non European Union countries

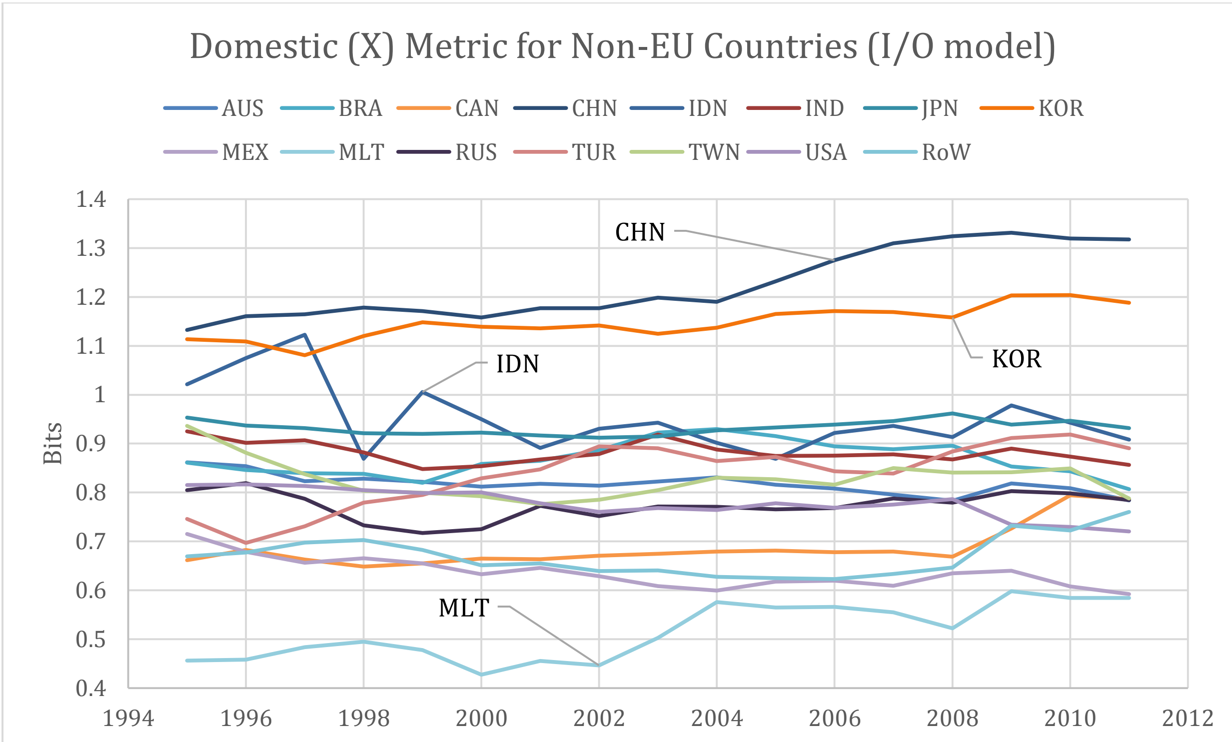


Figure 53: Input-output model average mutual constraint (X) time series for non European Union countries

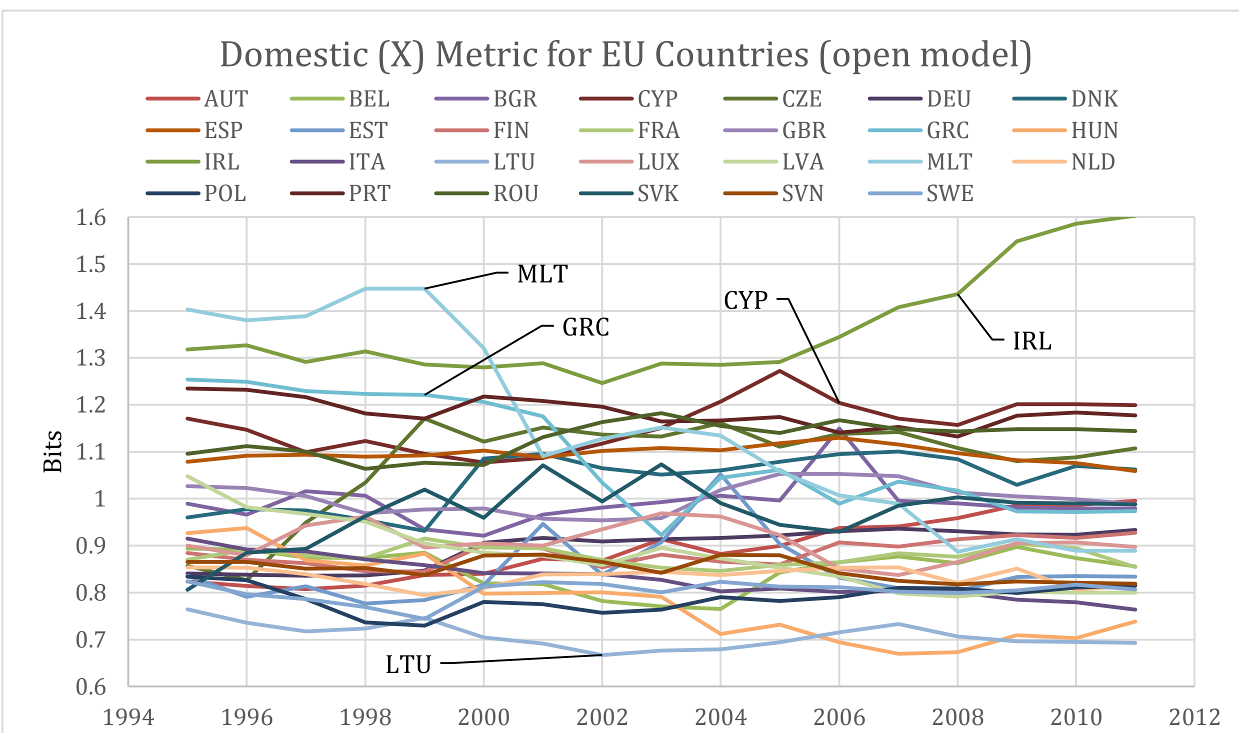


Figure 54: Open model average mutual constraint (X) time series for European Union countries

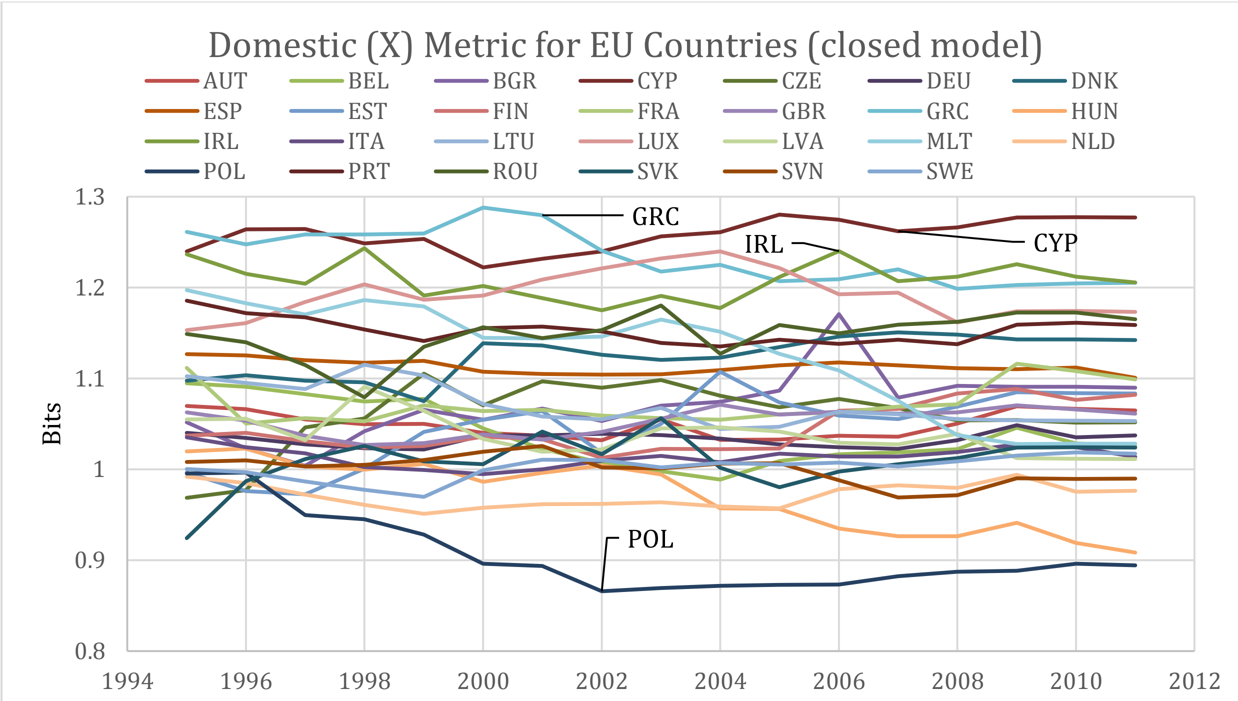


Figure 55: Closed model average mutual constraint (X) time series for European Union countries

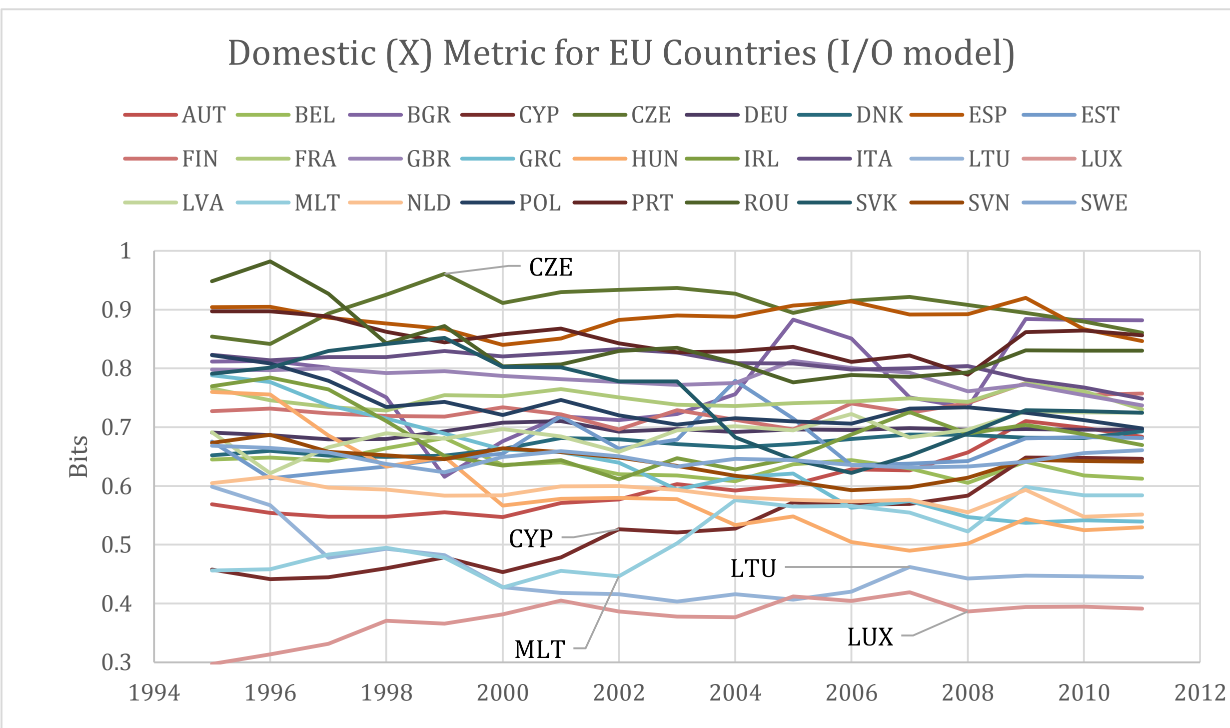


Figure 56: Input-output model average mutual constraint (X) time series for European Union countries

Chapter Four: Discussion of Results

GLOBAL MODEL RESULTS

The primary aim of this thesis is to explore the relationship between total energy consumption and economic complexity. Plotting total primary energy consumption against the calculated complexity metrics would seem a reasonable way to begin such an exploration. Figures 57 shows plots of total primary energy consumption against Ulanowicz's capacity, ascendancy, and reserve metrics. In all cases, there appears to be a nearly logarithmic relationship between the two variables. Results of Pearson product moment correlation testing are show in Table 4. It is apparent from these statistics that correlation is improved when the logarithm of the metrics is used, though correlation is strong and significant in all cases. Capacity and reserve uniformly show stronger correlation than ascendancy, and the input-ouput model yields stronger correlation than the other models. Apparent logarithmic correlation may simply be an artifact of a combination of strictly linear trends; after 2002, capacity and ascendancy increase at a greater rate than they did before 2002. A decrease in capacity and ascendancy can be seen between 2008 and 2009, likely corresponding to the "Great Recession".

Model	Variable 1	Variable 2	Correlation Coefficient	Significance
Global Open	Consumption	C	0.9732155	5.50E-11
		A	0.9699941	1.28E-10
		Phi	0.9743945	3.93E-11
		logC	0.9871781	2.28E-13
		logA	0.9835762	1.45E-12
		logPhi	0.9884706	1.03E-13
	logConsumption	C	0.9642649	4.65E-10
		A	0.9604635	9.82E-10
		Phi	0.9657168	3.42E-10
		logC	0.9826879	2.14E-12
		logA	0.9783031	1.15E-11
		logPhi	0.9843438	1.01E-12
Global Closed	Consumption	C	0.9732155	5.50E-11
		A	0.9699941	1.28E-10
		Phi	0.9763212	2.20E-11
		logC	0.9871781	2.28E-13
		logA	0.9835762	1.45E-12
		logPhi	0.9882527	1.19E-13
	logConsumption	C	0.9665187	2.87E-10
		A	0.9625455	6.59E-10
		Phi	0.967817	2.14E-10
		logC	0.9826879	2.14E-12
		logA	0.9783031	1.15E-11
		logPhi	0.9839103	1.24E-12
Global Input-Output	Consumption	C	0.9738853	4.55E-11
		A	0.9705984	1.10E-10
		Phi	0.9750963	3.20E-11
		logC	0.9875288	1.85E-13
		logA	0.9844478	9.62E-13
		logPhi	0.9886105	9.42E-14
	logConsumption	C	0.96498	4.01E-10
		A	0.9610907	8.73E-10
		Phi	0.9664546	2.92E-10
		logC	0.9830177	1.85E-12
		logA	0.9792383	8.28E-12
		logPhi	0.9844007	9.85E-13

Table 4: Pearson's product moment correlation coefficients and p-values for correlation test between energy consumption and weighted Ulanowicz test metrics, and log values of the same. Relatively high correlation values are highlighted

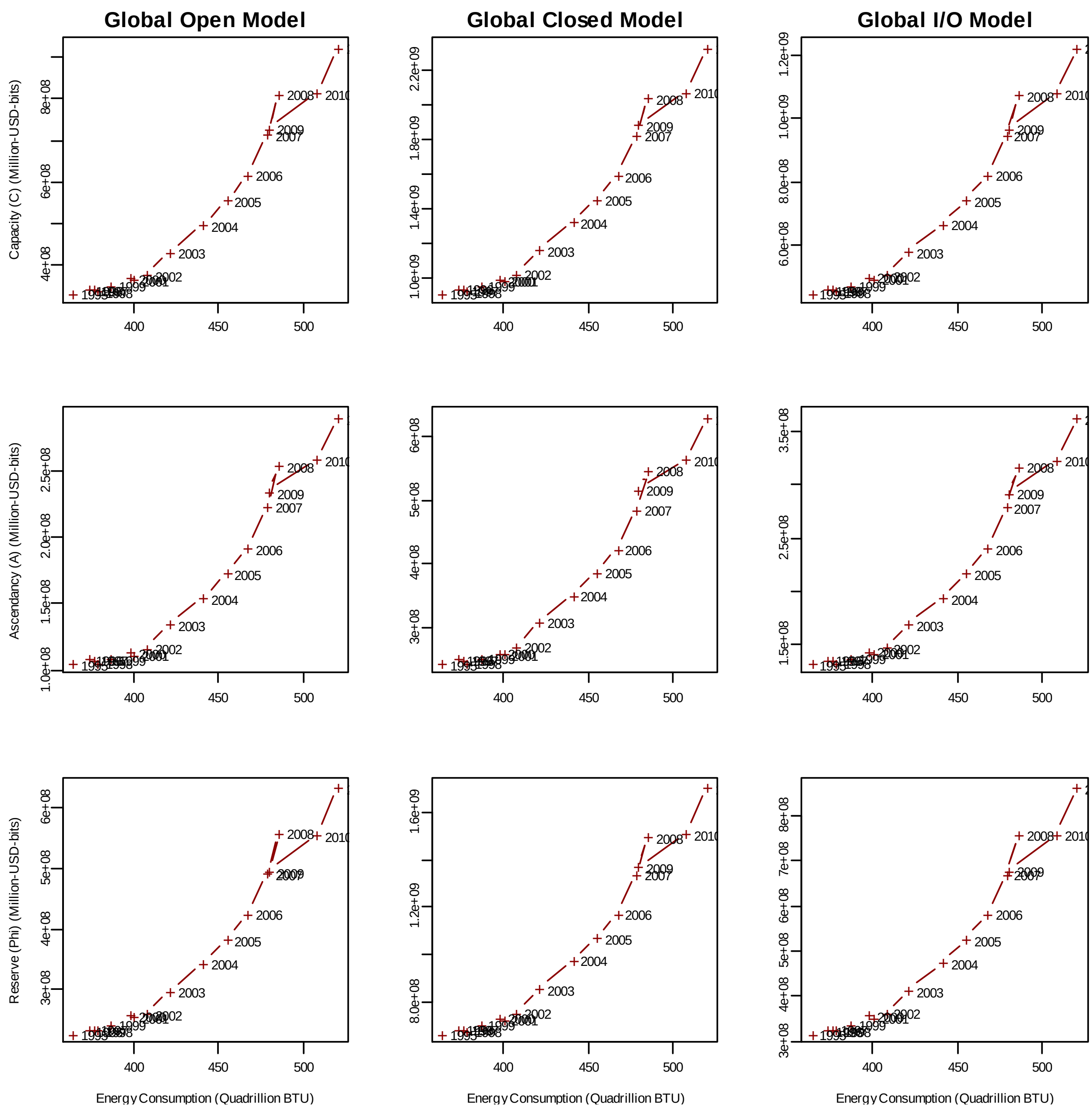


Figure 57: Plots of capacity (C), ascendancy (A), and reserve (φ) vs. total primary energy consumption for all global models

Though strong correlation is apparent between total primary energy consumption and the weighted Ulanowicz metrics, this is likely due to a confounding variable. As can be seen in Figure 58, there is also a strong relationship between total primary energy consumption and total system throughput, which is a large component of the weighted Ulanowicz metrics.

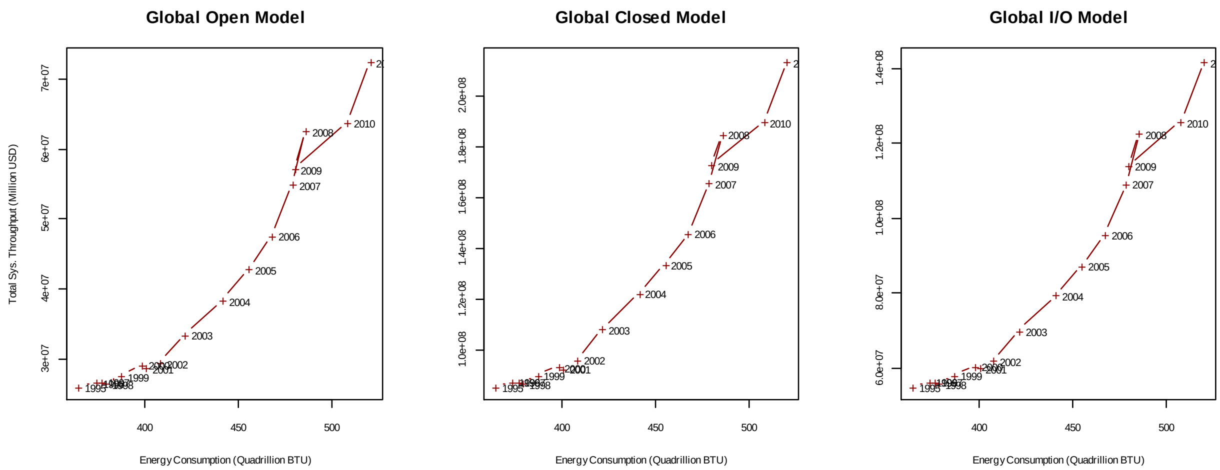


Figure 58: Plots of total system throughput vs. total primary energy consumption for all global models

For the global models, this same impact can be seen in the time series data (Figures 17 and 18), where the weighted metrics show a trend that is not apparent in the un-weighted metrics. The magnitude of total system throughput overwhelms the much smaller un-weighted metrics, and imparts trends that are accounted for strictly by changes in the magnitude of the economy, not in its underlying structure. While this sort of information may be useful for other analyses, the complexity of the relationships within the global economy is of greater concern for this analysis.

Figure 59 shows the relationships between total system throughput and the un-weighted Ulanowicz metrics: aggregate system indeterminacy (H), average mutual constraint (X), and conditional entropy (ψ). This effectively shows the relationship between an increasing amount of money in the economy, and economic complexity under the assumption of complete flow independence. There should be no confounding variable accounting for the relationship between these two variables.

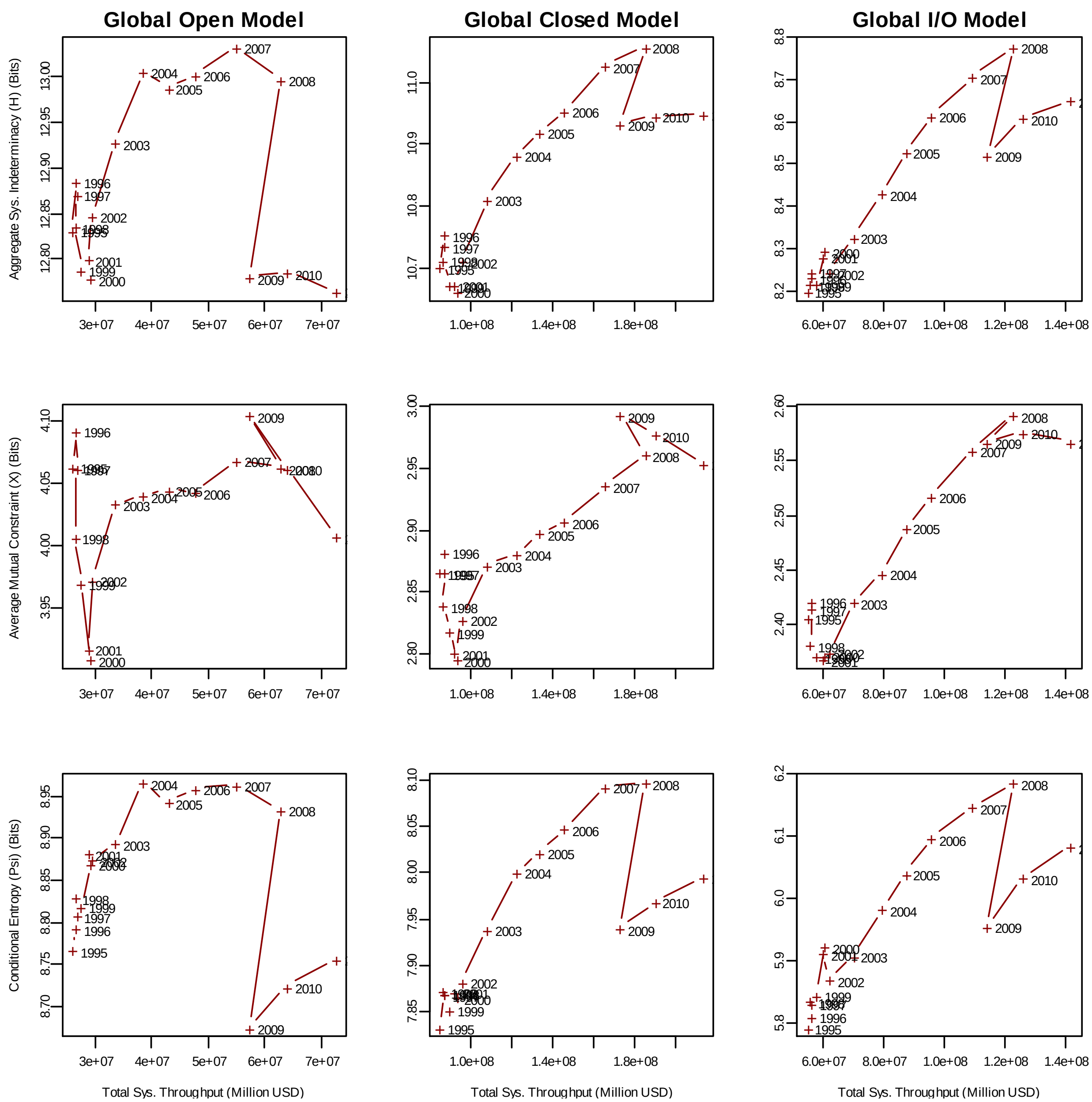


Figure 59: Plots of aggregate system indeterminacy (H), average mutual constraint (X), and conditional entropy (ψ) vs. total system throughput for all global models

The first observation that should be addressed in relation to Figure 60 is that the metric values are larger for the open models than for the closed and input-output models. The open models do not contain final demand or value added, so they are smaller in scope, and the higher value may seem counterintuitive. However, when the nature of the complexity metrics is considered, the apparent inversion seems to make sense. Value added dollar amounts tend to be significantly larger than other single flows, commonly above 50 percent of total output for an industry. The contribution of each table cell to H is:

$$h_i = -\frac{T_{ij}}{T_{..}} log\left(\frac{T_{ij}}{T_{ii}}\right) \tag{19}$$

where T_{ij} is the flow represented in the cell, and $T_{..}$ is the total system throughput. This function has its maximum value at e^{-1}, which corresponds to a probability of approximately 0.37. Probabilities greater than this yield increasingly smaller numbers. In a table of over 2 million cells, it is extremely unlikely that any one cell will have a value even remotely close to 37 percent of the total system throughput, so it is safe to say that, in this case, higher flows yield higher h_i values. The WIOT tables are mainly filled with numbers that correspond to very small probabilities, relative to those contributed by the few large numbers included in the value added row. Though a few relatively large numbers are added when moving from an open to closed model, the overwhelming majority of added flow values are between zero and one. The addition of the large values increases the total system throughput significantly, so all of the probabilities are now reduced. Essentially, the lower metric value is a result of the vast majority of the flows now contributing a decreased h_i value to the total metric. Conceptually, this now makes sense; adding a small set of high probability flows, and significantly lowering the probabilities of the other flows makes the system more determinate, and decreases its information content.

Nearly linear trends are apparent in the plots in Figure 60 for the closed and input-output models, particularly between the years 2002 and 2008. This period corresponds to a consistent rise in both total system throughput and increases in all metrics. Ulanowicz metric values tended to decrease between 1995 and 2002, while total system throughput increased slightly. Between 2008 and 2009, the effect of the Great Recession is readily apparent. Total system throughput decreases slightly, and metric values generally drop significantly. For the closed and input-output models, H values drop to levels seen around 2005, and ψ values drop to levels near those for 2003. Curiously, the X metric for 2009 is higher than in 2008 for the closed model, and no great decrease is seen for the input-output model. Trends for the open model are, in a very general sense, similar to those seen for the other models, but their magnitudes are distorted. The validity of the open model for assessing trends like those in Figure 60 is questionable, as it excludes a significant portion of the flows contained in each WIOT.

Table 5 shows results of Pearson product moment correlation testing for the relationship between the un-weighted Ulanowicz metrics and total primary energy consumption for the global models. Correlation is strong and significant for all closed and input-output metrics. No correlation is apparent between consumption and un-weighted metrics for the open model. The open model is unique in this analysis in that it does not take any wages, taxes, or final consumption into account. These transactions make up a significant portion of the total system throughput for the world, so it is perhaps not surprising that their exclusion yields results inconsistent with those from the other models. Costanza (1980) found that the dollar value of an industry's output correlated most strongly with the combined direct and embodied energy consumed in the production of that output when labor and government expenses were considered. The results here support those findings.

Model	Variable 1	Variable 2	Correlation Coefficient	Significance
Global Open	Consumption	H	0.1996281	4.42E-01
		X	0.2991808	2.43E-01
		Psi	0.02307037	9.30E-01
Global Closed	Consumption	H	0.8904384	1.67E-06
		X	0.8209065	5.38E-05
		Psi	0.815103	6.72E-05
Global Input-Output	Consumption	H	0.9337863	4.34E-08
		X	0.9120181	3.43E-07
		Psi	0.8827151	2.72E-06

Table 5: Pearson's product moment correlation coefficients and p-values for correlation test between energy consumption and un-weighted Ulanowicz test metrics.

These results mesh well with what can be seen in the plots of totally primary energy consumption versus the un-weighted Ulanowicz metrics, shown in Figure 61. As with the plots in

Figure 60, a nearly linear relationship can be seen between the two variables for the closed and input-output models, particularly for the H metrics. Trends similar to those in the relations between the un-weighted metrics and total system throughput are once again apparent when the metrics are compared to energy consumption. A steady increase in both consumption and metric values is seen for years 2002 through 2008. Between 2008 and 2009, consumption decreased slightly, while H and X decrease more significantly.

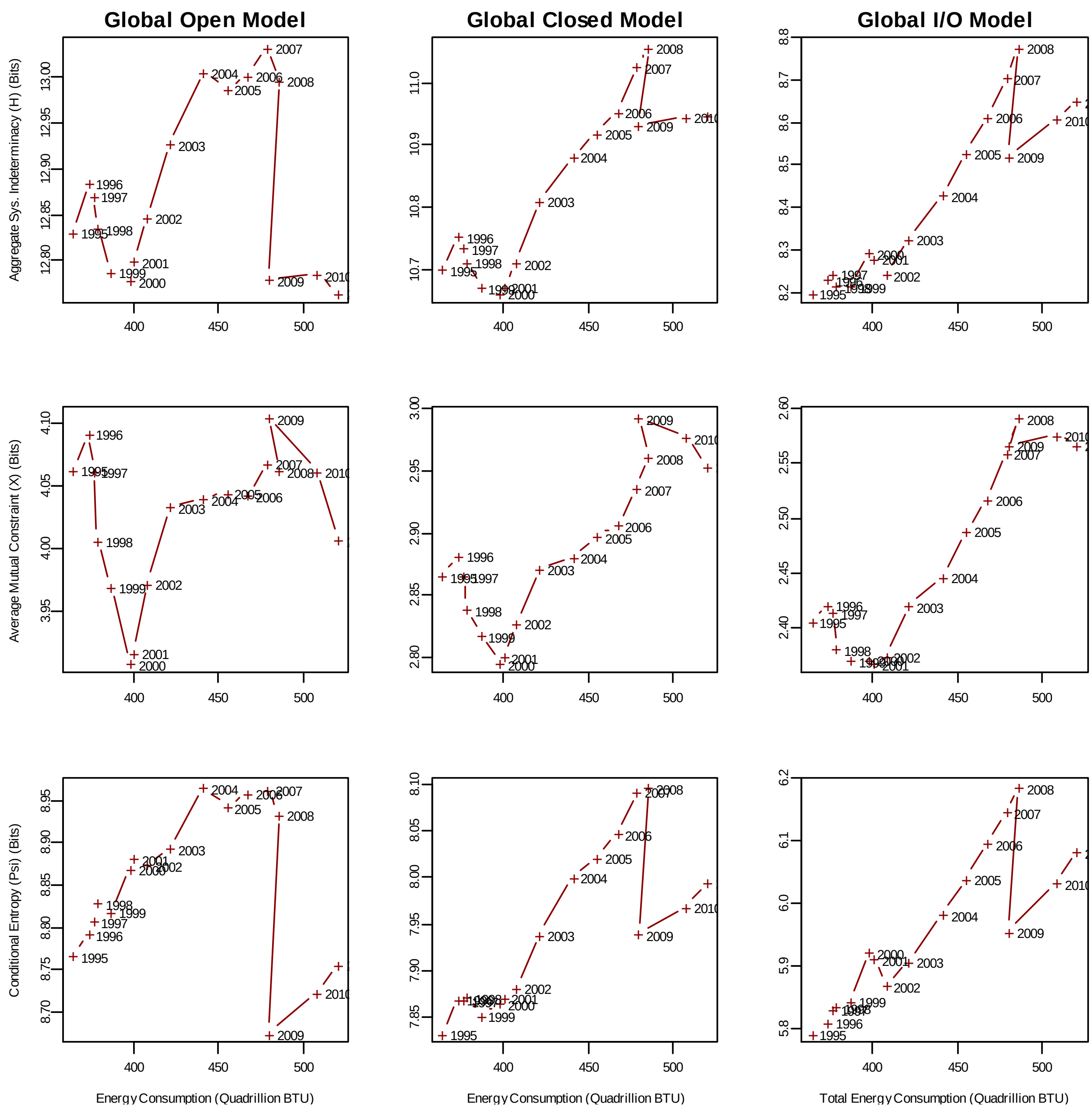


Figure 60: Plots of aggregate system indeterminacy (H), average mutual constraint (X), and conditional entropy (ψ) vs. total primary energy consumption for all global models

As stated above, Ulanowicz argues that H is a system's "capacity for evolution or self-organization", and that its two components, X and ψ, represent what is "regular, orderly, coherent, and efficient", and what is "irregular, disorderly, incoherent, and inefficient" about the system, respectively (Ulanowicz et al., 2009). Given this, it is interesting to observe the difference in the magnitude of the drop in value between 2008 and 2009 for each metric. Where ψ drops substantially, X drops very little or increases, depending on the model used to calculate the metric. This lends credence to the idea that the conditional entropy, ψ, functions as a system's capacity to adapt to novel situations. During the Great Recession, it appears that the greater decrease in ψ made up the largest portion of the overall decrease in overall system complexity, as measured by H, effectively buffering the system and allowing for minimal disruption to overall system organization, measured by X.One potential drawback to Ulanowicz's un-weighted metrics is that they contain no information about their magnitude in any absolute sense, as their maximum values are not indicated. Normalizing the metrics to their maximum values, as calculated by equation 4, should yield additional information about the magnitude of the metric within a defined range. Normalizing average mutual constraint to the maximum information entropy for the system, as in equation 18, gives a quantity known as the relative entropy. This value is plotted against total primary energy consumption in Figure 61. While the values of the relative entropy metric may contain more useful information, the general trends are of course identical to those seen for non-normalized metric. Further, it is not clear that all metrics should be normalized by the same value. The average mutual constraint has its maximum value at half of the maximum information entropy, meaning that the maximum relative entropy value would be 0.5.

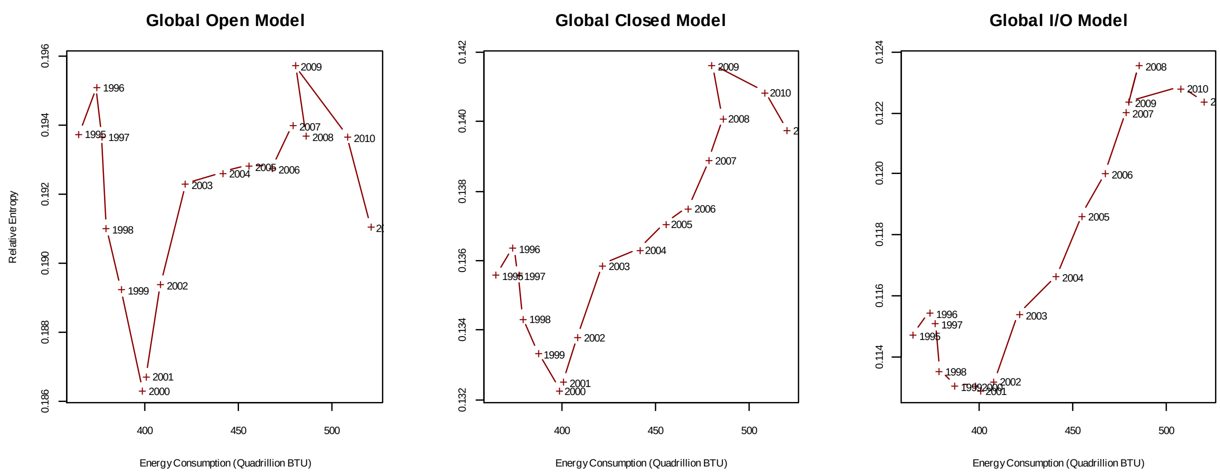


Figure 61: Plots of relative entropy vs. total primary energy consumption for all global models

Ulanowicz's metrics each describe a different facet of system complexity. Through equations 14 and 15, X and ψ form the basis by which the "number of roles" and "link density" can be calculated for the system. The number of roles can be thought of as a measure of system hierarchy, and the link density can be thought of as its connectedness. Figure 62 shows the number of roles plotted against link density for each global model.

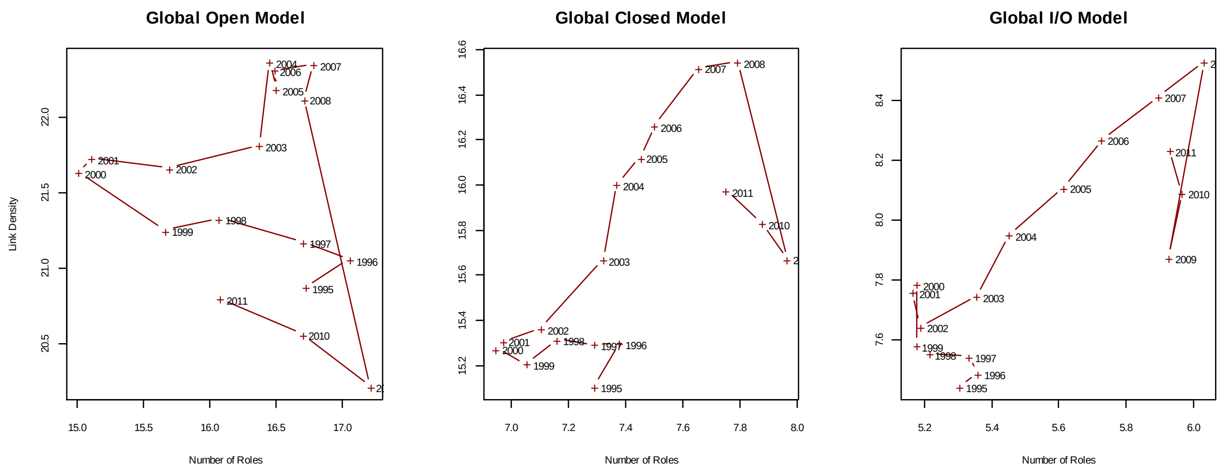


Figure 62: Plots of effective connectivity (m) vs. number of roles (n) for all global models

Between 2002 and 2008, a strong linear trend is again apparent. In this case, both link density and the number of roles are increasing consistently for the closed and input-output models. Between 2008 and 2009, the number of roles decreases only slightly and the link density drops to levels equivalent to those seen between 2003 and 2004. By 2011, the link density has recovered somewhat. This suggests that the global economy dealt with the shock of the Great Recession by decreasing connectivity, rather than minimizing specialization and removing levels of hierarchy in production.

It is perhaps noteworthy that the strongest linear trend noted in all of the above plots occurs for the years between 2002 and 2008. This may correspond to a period of increasing energy cost share, which is the portion of global Gross Domestic Product dedicated to the production of energy (King; Maxwell). According to Tainter, systems dependant upon lower-gain energy supplies require greater organization and efficiency, and new levels of hierarchy to function effectively (Tainter et al., 2003). Given the decreasing gain of the global energy supply between 2002 and 2008, the consistent increase in all of the information entropy based metrics makes sense as an increase in economic complexity. Alternately, it is possible that the steadily increasing global total system throughput and total energy consumption during these years led directly to the increases in connectivity and hierarchy. In this case increased globalization would have been a response to a positive condition rather than a negative one.

Domestic Model Results

Additional information on the relationship between energy use and complexity can be gleaned from the domestic model results. Figures 63, 64 and 65 are scatter plots of the number of roles versus the link density for each country for each year. Data points from countries that are net producers of energy are highlighted in red. Scatter plots for each year, and scatter plots with each country highlighted, are included in Appendix C. In figures 63 and 64, the plots for the open and closed models, the points generally cluster along a linear trend that roughly connects the maximum observed values for each variable. Countries that fall outside this cluster can generally be identified in the time series data as well. For instance, the open model data for Luxembourg cluster together at low link density and low levels of hierarchy. Data for countries that are net energy producers appear to cluster more tightly along the center of the general trend line than data from countries that are net consumers of energy. The significance of this is unclear.

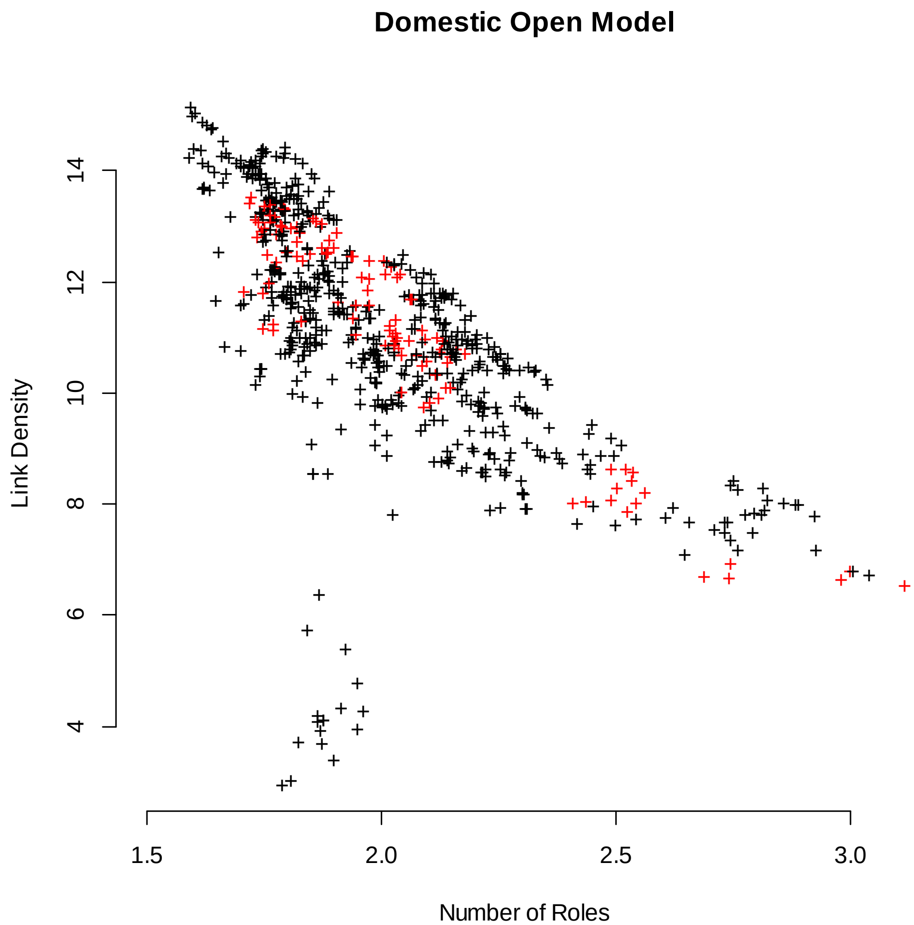


Figure 63: Scatter plot of effective connectivity (m) vs. number of roles (n), each year for each country, calculated for the open model. Net producers are plotted in red. Maximum n and m values are 35.

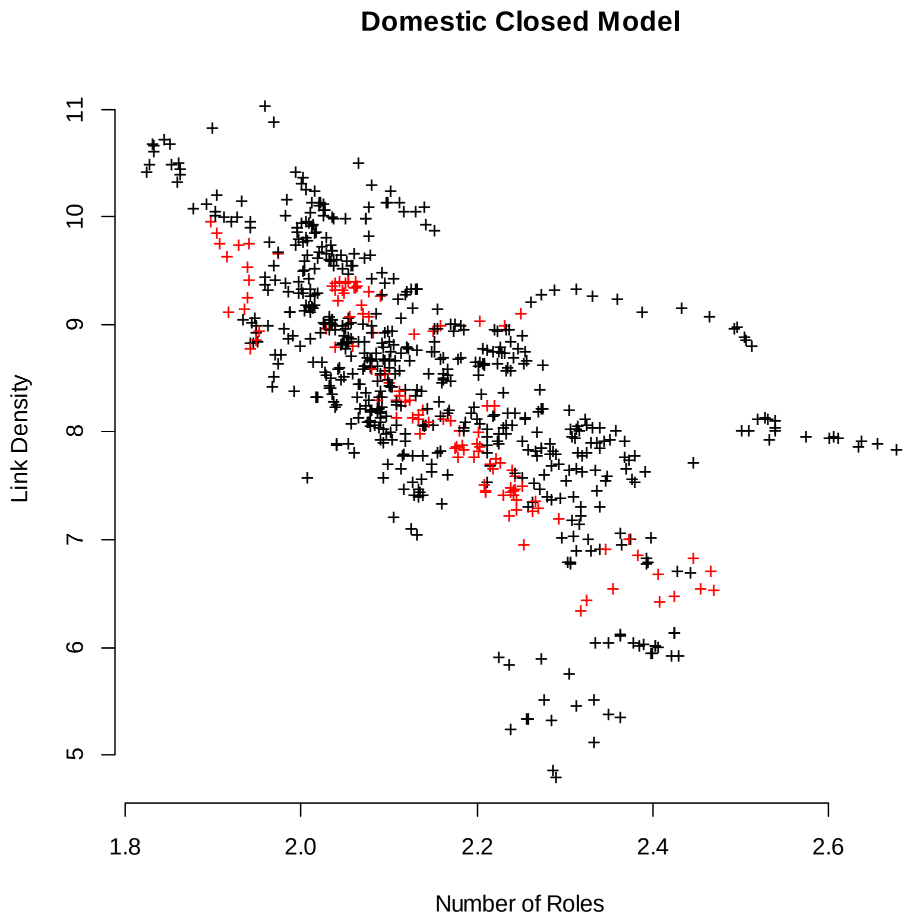


Figure 64: Scatter plot of effective connectivity (m) vs. number of roles (n), each year for each country, calculated for the closed model. Net producers are plotted in red. Maximum n and m values are 38.

The scatter plot shown in Figure 64, made using the input-output model results, shows a much different trend than the plots for the other two domestic models. The data points generally cluster along a line with a positive slope, rather than along a line with a negative slope. In this case, countries with a larger number of roles also have greater link density. The slope of the general trend is greater than one, such that a country with 0.2 additional roles has a link density that is higher by approximately 1.

In the case of both the open and closed domestic models, imports and exports are not included, while they are considered as exogenous inputs and outputs for the input-output model.

The open and closed models represent only the economic activity happening within the borders of a county, and their scatter plots show a trend of substitution between hierarchy and connectivity. In this case, countries with a relatively low number of roles have a relatively high link density, and vice versa. This likely indicates that, during the time period covered by the WIOD, the overall complexity of an individual country's economy was driven largely by interactions with other countries, rather than by changes within its borders. During the years covered by the WIOD, significant globalization occurred, so this is not an unexpected result.

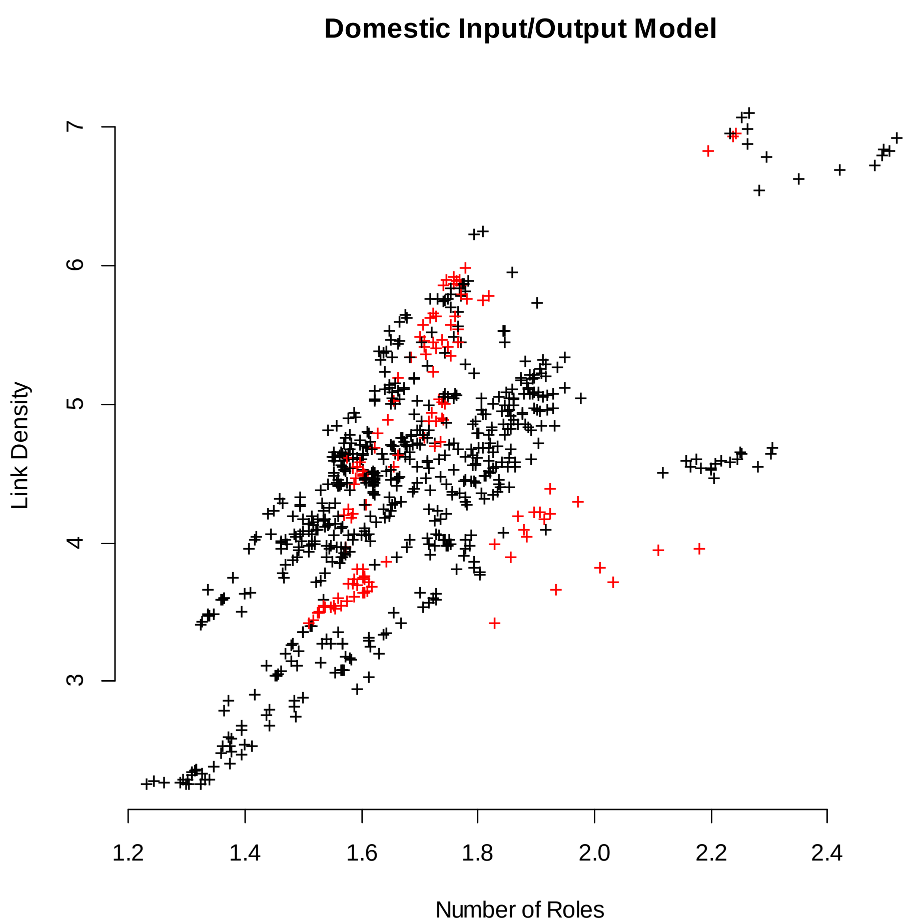


Figure 65: Scatter plot of effective connectivity (m) vs. number of roles (n), each year for each country, calculated for the input-output model. Net producers are plotted in red. Maximum n and m values are 70.

Chapter Five: Conclusions

Conclusions

This thesis is largely an exploration of the relationship between economic complexity and energy consumption, with an eye toward Joseph Tainter's theory that such a relationship is compulsory. If this theory is correct, the inevitable occurrence of social problems necessitates ever increasing energy consumption, and ideas about sustainability are brought into question. Tainter's theory is an explicit statement of causation, where complexity is not simply a byproduct of growth, but a requirement for to continued existence of a society. In this way, energy conservation becomes a fruitless endeavor, and even technologies that improve energy efficiency do not change the long-term outlook.

Energy use is reasonably straightforward to measure, but economic complexity is a somewhat ambiguous concept. In his efforts to quantitatively describe ecosystems as networks, Robert Ulanowicz devised a series of information entropy based metrics that prove useful as measures of some of the many facets of complexity. These metrics lend themselves well to the analysis of economic data in the form of input-output tables. The World Input-Output Database contains such tables constructed for the global economy, for the years 1995 through 2011.

Applying Ulanowicz's metrics to the data contained in the World Input-Output Tables yields valuable insight into the structure of the global economy, and provides a series of descriptive measures for comparison to energy use. Ulanowicz's weighted metrics, capacity, ascendancy, and reserve, tend to provide more information about the scale of the economy than about its fundamental structure and organization, so un-weighted metrics are considered more accurate measures of complexity. When calculated using closed and input-output corrected models, these metrics correlate strongly to energy use. Since there is also a strong relationship between total system throughput and energy use, it is difficult to determine exactly what that correlation reflects.

Two notable trends are apparent in the complexity results for the global closed and input-output models; a steady increase in both energy use and complexity occurred between 2002 and 2008, and a marked decrease in complexity occurred between 2008 and 2009. The trend between

2002 and 2008 is coincident with a period of increasing energy cost share. It is unclear whether complexity increased in response to rising energy costs, or if it was a result of increases in globalization and overall spending. The drop between 2008 and 2009 is clearly coincident with the Great Recession. It is perhaps interesting to note that the complexity metrics for this period reflect a greater drop in connectivity than in hierarchy, suggesting that global economy dealt with the shock of the Great Recession by decreasing connectivity, rather than minimizing specialization and removing levels of hierarchy in production.

When complexity metrics are calculated on the national level, additional relationships are apparent. It appears that countries have similar overall levels of internal complexity, differing mainly in their relative levels of internal hierarchy and connectivity. Growth in overall complexity has occurred largely as result of trade and globalization for the time period studied. Net producers of energy appear to cluster along the center of each general trend line, but the reason for this is not clear at this time.

While this thesis does not provide strong evidence in support of or against Tainter's theory, it does begin to shed some light on the relationship between economic complexity and energy use. The complexity metrics described here may be of more use as economic descriptive statistics than they are for comparison to other variables.

Appendices

APPENDIX A: DATA USED IN CREATION OF WORLD INPUT-OUTPUT TABLES

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Australia		SUT (106c * 106i)							SUT (233c * 53i)	SUT (233c * 53i)			
Austria	SUT (59c * 59i)		SUT (59c * 59i)		SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)		
Belgium	SUT (59c * 59i)		SUT (59c * 59i)		SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)			
Brazil						SUT (110c * 55i)	SUT (110c * 55i)	SUT (110c * 55i)	SUT (110c * 55i)	SUT (110c * 55i)	SUT (110c * 55i)	SUT (110c * 55i)	
Bulgaria						SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)			
Canada			SUT (BP) (473c*122i)	SUT (BP) (473c*122i)	SUT (BP) (473c*122i)	SUT (BP) (473c*122i)	SUT (BP) (473c*122i)	SUT (BP) (473c*122i)	SUT (BP) (473c*122i)	SUT (BP) (473c*122i)	SUT (BP) (473c*122i)	SUT (BP) (473c*122i)	
China			SUT(PR) (40c * 40i) & IO(PR) (124c * 124c)					SUT(PR) (42c * 42i) & IO(PR) (122c * 122c)					SUT(PR) (42c * 42i) & IO(PR) (135c * 135c)
Cyprus*						SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
Czech Republic	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)		
Denmark		SUT (59c * 59i)			SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)		
Estonia			SUT (59c * 59i)		SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
Finland	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
France	SUT (59c * 59i)		SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
Germany	SUT (59c * 59i)		SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
Greece						SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
Hungary				SUT (59c * 59i)	SUT (59c * 59i)			SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
India				SUT(FC) (115c * 115i)					SUT(FC) (130c * 130i)			SUT(FC) (130c * 130i)	
Indonesia	IO (172c * 172c)					IO (175c * 175c)					IO (175c * 175c)		

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Ireland						SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)			SUT (59c * 59i)		
Italy	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)		
Japan	IO(PR) (108i * 108i)					IO(PR) (108i * 108i)							
Korea	IO(PR) (402c*402i)					IO(PR) (404c*404i)					IO(PR) (403c*403i)		
Latvia													
Lithuania		SUT (59c * 59i)		SUT (59c * 59i)					SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)		
Luxembourg	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
Malta						SUT (59c * 59i)	SUT (59c * 59i)						
Mexico									SUT (79c * 79i)				
Netherlands	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
Poland		SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)						SUT (59c * 59i)		
Portugal	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
Romania						SUT (59c * 59i)			SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
Russia	SUT (110c *59i)												
Slovak Republic	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
Slovenia						SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
Spain	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
Sweden	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	
Taiwan		IO (596c*160i)					IO (610c*160i)					IO (554c*165i)	
Turkey		SUT(PR) (97c*97i)		SUT (97c*97i)				SUT (59c*59i)					
United Kingdom	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)	SUT (59c * 59i)				
USA	SUT(PR) (130c * 130i)	SUT(PR) (66c * 65i)	SUT(PR) (66c * 65i)	SUT(PR) (66c * 65i)	SUT(PR) (66c * 65i)	SUT(PR) (66c * 65i)	SUT(PR) (66c * 65i)	SUT(PR) (66c * 65i)	SUT(PR) (66c * 65i)	SUT(PR) (66c * 65i)	SUT(PR) (66c * 65i)		

APPENDIX B: MATLAB SCRIPTS USED FOR CALCULATION OF ULANOWICZ METRICS

Global Open Model

```
%Stephen Bond
%Feb 24 2015
%Global Metrics, Open Model
%
%This code calculates Ulanowicz metrics for the global open model
%case, from WIOT Excel tables for each year.

clear
clc

%Set working directory
directory = uigetdir();
cd(directory)

%Get all the Excel files in the working directory
files = dir('*.xlsx');

%Matrix for storing results
metrics = zeros(length(files),7);

%Initiate counter that increases for every file, used for getting metrics
%into output table
counter = 1;

%Loop through Excel files in directory and load into cell tables
for file = files'
    T = xlsread(file.name,'E7:BCI1441'); %inter-industry flows

    %Get years for results matrix
    rawyear = file.name(5:6);
    numyear = str2num(rawyear);
    if numyear<50
        year = sprintf('20%s', rawyear);
    else
        year = sprintf('19%s', rawyear);
    end %end if statement for year assignment

    %Get number of rows and columns
    metrics(counter,1) = str2num(year);
    numrows = size(T,1);
    numcols = size(T,2);
    TST = sum(sum(T)); %Total system throughput (sum of all of flows)

    %Set initial variable metrics to zero.
    C = 0;
    Phi = 0;
    A = 0;
```

```
    %Loop through entires in WIOT table
    for i = 1:numrows
        for j = 1:numcols
            %Log(0)is not defined, so only calculate if flow is greater
            %than 0
            if T(i,j)>0
                %Ulanowicz Capacity
                C = C - T(i,j)*log2(T(i,j)/TST);
                %Ulanowicz Reserve
                Phi = Phi - T(i,j)*log2(T(i,j)^2/(sum(T(i,:))*sum(T(:,j))));
                %Ulanowicz Ascendency
                A = A + T(i,j)*log2(T(i,j)*TST/(sum(T(i,:))*sum(T(:,j))));

            %If flow is zero, metrics remain the same
            else
                %Ulanowicz Capacity
                C = C + 0;
                %Ulanowicz Reserve
                Phi = Phi  + 0;
                %Ulanowicz Ascendency
                A = A + 0;

            end %end if statement
        end %end loop through columns
    end %end loop through rows

    %Ulanowicz metrics scaled to TST
    H = C/TST;
    Psi = Phi/TST;
    X = A/TST;

    %Add metrics to results matrix and sort on date column
    metrics(counter,2) = C;
    metrics(counter,3) = Phi;
    metrics(counter,4) = A;
    metrics(counter,5) = H;
    metrics(counter,6) = Psi;
    metrics(counter,7) = X;
    metsort = sortrows(metrics);

    %Increase counter
    counter = counter+1;

end %end loop through files

%Write metrics to a .csv file in the working directory
header = {'Year','C','Phi','A','H','Psi','X'};
metricsout = [header; num2cell(metsort)];
numoutcols = size(metricsout,2);
fid = fopen('GlobalOpen_Output.csv', 'w');
headerrpt = repmat('%s,',1,numoutcols-1);
metricrpt = repmat('%f,',1,numoutcols-1);
fprintf(fid,[headerrpt,'%s\n'],metricsout{1,:});
for q=2:size(metricsout,1)
```

```
    fprintf(fid,[metricrpt,'%f\n'],metricsout{q,:});
end
fclose(fid);
```

Global Closed Model

```
%Stephen Bond
%Feb 24 2015
%Global Metrics, Open Model
%
%
%This script calculates Ulanowicz metrics for the global open
%model case, from WIOT Excel tables for each year.

clear
clc

%Set working directory - this should be a directory with only the WIOT
%Excel files
%cd('/Users/StephenBond/Dropbox/Academic/Thesis/Workspace/International')
directory = uigetdir();
cd(directory)

%Get all the Excel files in the working directory
files = dir('*.xlsx');

%List all countries in WIOT files and set number of countries as a variable
country={'AUS','AUT','BEL','BGR','BRA','CAN','CHN','CYP','CZE','DEU','DNK','E
SP','EST','FIN','FRA',...
'GBR','GRC','HUN','IDN','IND','IRL','ITA','JPN','KOR','LTU','LUX','LVA','MEX'
,'MLT','NLD','POL','PRT','ROU','RUS',...
'SVK','SVN','SWE','TUR','TWN','USA','RoW'};
countries = length(country);

%Matrix for storing results
metrics = zeros(length(files),7);

%Initiate counter
counter = 1;

%Loop through WIOT files
for file = files'
    T = xlsread(file.name,'E7:BKF1448'); %Read Excel file into matrix
    %Get years for results output
    rawyear = file.name(5:6);
    numyear = str2num(rawyear);
    if numyear<50
        year = sprintf('20%s', rawyear);
    else
        year = sprintf('19%s', rawyear);
    end %end if statement for year assignment
```

```
T(1436,:) = []; %Remove subtotal row to avoid double counting
T(1439,:) = []; %Remove spending abroad row - sums to negative number
%Add WIOT year to first column of results matrix
metrics(counter,1) = str2num(year);
numrows = size(T,1);
numcols = size(T,2);
TST = sum(sum(T)); %Total system throughput (sum of all of flows)

%Loop through countries and set each capital formation and inventory
%change column to 0. They will not be included in calculations, as they
%sum to negative values
for l=1:countries;
    formation = (l*4)+1435+(l-1);
    changes = (l*5)+1435;
    T(:,formation)=[0];
    T(:,changes)=[0];
end %End data removal loop

%Set initial variable metrics to zero.
C = 0;
Phi = 0;
A = 0;

%Loop through entires in WIOT table
for i = 1:numrows
    for j = 1:numcols
        %Log(0)is not defined, so only calculate if flow is greater
        %than 0
        if T(i,j)>0
            %Ulanowicz Capacity
            C = C - T(i,j)*log2(T(i,j)/TST);
            %Ulanowicz Reserve
            Phi = Phi-T(i,j)*log2(T(i,j)^2/sum(T(i,:),2)/sum(T(:,j),1));
            %Ulanowicz Ascendency
            A = A + T(i,j)*log2(T(i,j)*TST/sum(T(i,:),2)/sum(T(:,j),1));

        %If flow is zero, metrics remain the same
        else
            %Ulanowicz Capacity
            C = C + 0;
            %Ulanowicz Reserve
            Phi = Phi  + 0;
            %Ulanowicz Ascendency
            A = A + 0;
        end %end if statement
    end %end loop through columns
end %end loop through rows

%Ulanowicz metrics scaled to TST
H = C/TST;
Psi = Phi/TST;
X = A/TST;

%Add metrics to results matrix and sort by year
metrics(counter,2) = C;
metrics(counter,3) = Phi;
```

```
    metrics(counter,4) = A;
    metrics(counter,5) = H;
    metrics(counter,6) = Psi;
    metrics(counter,7) = X;
    metsort = sortrows(metrics);

    %Increase counter
    counter = counter+1;
end %end loop through files

%Write metrics to a .csv file in the working directory
header = {'Year','C','Phi','A','H','Psi','X'};
metricsout = [header; num2cell(metsort)];
numoutcols = size(metricsout,2);
fid = fopen('GlobalClosed_Output.csv', 'w');
headerrpt = repmat('%s,',1,numoutcols-1);
metricrpt = repmat('%f,',1,numoutcols-1);
fprintf(fid,[headerrpt,'%s\n'],metricsout{1,:});
for q=2:size(metricsout,1)
    fprintf(fid,[metricrpt,'%f\n'],metricsout{q,:});
end
fclose(fid);
```

Global Input-Output Model

```
%Stephen Bond
%Mar 21 2015
%Global Metrics, Input-Output Model
%
%
%This script calculates Ulanowicz metrics for the global case,
%treating value added as inputs and final demand as outputs.
%Extracts data from WIOT Excel tables for each year.

clear
clc

%Set working directory - this should be a directory with only the WIOT
%Excel files
%cd('/Users/StephenBond/Dropbox/Academic/Thesis/Workspace/International')
directory = uigetdir();
cd(directory)

%Get all the Excel files in the working directory
files = dir('*.xlsx');

%List all countries in WIOT files and set number of countries as a variable
country={'AUS','AUT','BEL','BGR','BRA','CAN','CHN','CYP','CZE','DEU',...
    'DNK','ESP','EST','FIN','FRA','GBR','GRC','HUN','IDN','IND','IRL',...
    'ITA','JPN','KOR','LTU','LUX','LVA','MEX','MLT','NLD','POL','PRT',...
    'ROU','RUS','SVK','SVN','SWE','TUR','TWN','USA','RoW'};
countries = length(country);
```

```
%Matrix for storing results
metrics = zeros(length(files),7);

%Initiate counter
counter = 1;

%Loop through WIOT files
for file = files'
    %Read intermediate values into matrix
    TT = xlsread(file.name,'E7:BCI1441');
    %Read input values into matrix
    I_raw = xlsread(file.name,'E1443:BCI1448');
    %Read output values into matrix
    O_raw = xlsread(file.name,'BCJ7:BKF1441');

    %collapse input and output matrices into vectors of sums
    I = sum(I_raw, 1);
    O = sum(O_raw, 2);

    %Get years for results output
    rawyear = file.name(5:6);
    numyear = str2num(rawyear);
    if numyear<50
        year = sprintf('20%s', rawyear);
    else
        year = sprintf('19%s', rawyear);
    end %end if statement for year assignment

    %Set initial variable metrics to zero.
    C = 0;
    Phi = 0;
    A = 0;
    OO = 0;

    %Handle negatives in input by zeroing out negative and
    %adding it's opposite to relevant output
    for p = 1:length(I)
        if I(p) < 0
            O(p) = O(p)+abs(I(p));
            I(p) = 0;
        else
            I(p) = I(p);
        end
    end

    %Handle negatives in output by zeroing out negative and
    %adding it's opposite to relevant input
    for q = 1:length(O)
        if O(q) < 0
            I(q) = I(q)+abs(O(q));
            O(q) = 0;
        else
            O(q) = O(q);
        end
```

```
end

%Calculate open system add-on from inputs
for m = 1:length(I)
    if I(m) == 0
        OO = OO;
    else
        OO = OO-I(m)*log2(I(m)/(I(m)+sum(TT(:,m))));
    end
end

%Calculate open system add-on from outputs
for n = 1:length(O)
    if O(n) == 0
        OO = OO;
    else
        OO = OO-O(n)*log2(O(n)/(O(n)+sum(TT(n,:))));
    end
end

%Add inputs and outputs to intermediate matrix
T = [TT O;
    I 0];

%Add WIOT year to first column of results matrix
metrics(counter,1) = str2num(year);

%Runs through only intermediate flows, but uses all for TST
numrows = size(TT,1);
numcols = size(TT,2);
TST = sum(sum(TT)) + sum(I); %Total system throughput

%Loop intermediate through entries in WIOT table
for i = 1:numrows
    for j = 1:numcols
        %Log(0)is not defined, so only calculate if flow is greater
        %than 0
        if T(i,j)>0
            %Ulanowicz Capacity
            C = C - T(i,j)*log2(T(i,j)/TST);
            %Ulanowicz Reserve
            Phi = Phi-T(i,j)*log2(T(i,j)^2/sum(T(i,:),2)/sum(T(:,j),1));
            %Ulanowicz Ascendency
            A = A + T(i,j)*log2(T(i,j)*TST/sum(T(i,:),2)/sum(T(:,j),1));

        %If flow is zero, metrics remain the same
        else
            %Ulanowicz Capacity
            C = C + 0;
            %Ulanowicz Reserve
            Phi = Phi  + 0;
            %Ulanowicz Ascendency
            A = A + 0;
        end %end if statement
    end %end loop through columns
```

```
    end %end loop through rows

    %Add open model corrections to metrics
    C = C + 2*OO;
    Phi = Phi + OO;
    A = A + OO;

    %Unscaled Ulanowicz metrics
    H = C/TST;
    Psi = Phi/TST;
    X = A/TST;

    %Add metrics to results matrix and sort by year
    metrics(counter,2) = C;
    metrics(counter,3) = Phi;
    metrics(counter,4) = A;
    metrics(counter,5) = H;
    metrics(counter,6) = Psi;
    metrics(counter,7) = X;
    metsort = sortrows(metrics);

    %Increase counter
    counter = counter+1;
end %end loop through files

%Write metrics to a .csv file in the working directory
header = {'Year','C','Phi','A','H','Psi','X'};
metricsout = [header; num2cell(metsort)];
numoutcols = size(metricsout,2);
fid = fopen('Global_IO_Output.csv', 'w');
headerrpt = repmat('%s,',1,numoutcols-1);
metricrpt = repmat('%f,',1,numoutcols-1);
fprintf(fid,[headerrpt,'%s\n'],metricsout{1,:});
for q=2:size(metricsout,1)
    fprintf(fid,[metricrpt,'%f\n'],metricsout{q,:});
end
fclose(fid);
```

Domestic Open Model

```
%Stephen Bond
%March 1 2015
%Domestic Open Metrics
%
%
%This code calculates Ulanowicz metrics for each country
%from WIOT Excel tables for each year.

clear
clc
```

```
%Set working directory
%cd('/Users/StephenBond/Dropbox/Academic/Thesis/Workspace/International')
directory = uigetdir();
cd(directory);

%List all countries in WIOT files and set number of countries as a variable
country={'AUS','AUT','BEL','BGR','BRA','CAN','CHN','CYP','CZE','DEU','DNK','E
SP','EST','FIN','FRA',...
'GBR','GRC','HUN','IDN','IND','IRL','ITA','JPN','KOR','LTU','LUX','LVA','MEX'
,'MLT','NLD','POL','PRT','ROU','RUS',...
'SVK','SVN','SWE','TUR','TWN','USA','RoW'};
countries = length(country);

%Loop through Excel files in directory and load into cell tables
files = dir('*.xlsx');

%Initialize counter
counter = 1;

%create results matrices for each metric
metrics_C = zeros(length(files), countries);
metrics_Phi = zeros(length(files), countries);
metrics_A = zeros(length(files), countries);
metrics_H = zeros(length(files), countries);
metrics_Psi = zeros(length(files), countries);
metrics_X = zeros(length(files), countries);

%loop through Excel files in directory and load into cell tables
for file = files'
    T = xlsread(file.name,'E7:BCI1441');
    %Get years for results output
    rawyear = file.name(5:6);
    numyear = str2num(rawyear);
    if numyear<50
        year = sprintf('20%s', rawyear);
    else
        year = sprintf('19%s', rawyear);
    end %end if statement for year assignment

    %add WIOT year to first column of each results matrix
    metrics_C(counter,1) = str2num(year);
    metrics_Phi(counter,1) = str2num(year);
    metrics_A(counter,1) = str2num(year);
    metrics_H(counter,1) = str2num(year);
    metrics_Psi(counter,1) = str2num(year);
    metrics_X(counter,1) = str2num(year);

    %Loop through countries and define row and column boundaries for each
    for l = 1:countries
        domesticmin = (l-1)*35+1;
        domesticmax = l*35;
        %create matrix with only domestic flows
        subT = T(domesticmin:domesticmax, domesticmin:domesticmax);
        numrows = size(subT,1);
        numcols = size(subT,2);
```

```
        TST = sum(sum(subT));

        %Set initial variable metrics to zero.
        C = 0;
        Phi = 0;
        A = 0;
        H = 0;
        Psi = 0;
        X = 0;

        %Loop through entires in WIOT table
        for i = 1:numrows
            for j = 1:numcols
                %Log(0)is not defined, so only calculate if flow is greater
                %than 0
                if subT(i,j)>0
                    %Ulanowicz Capacity
                    C = C - subT(i,j)*log2(subT(i,j)/TST);
                    %Ulanowicz Reserve
                    Phi = Phi -
subT(i,j)*log2(subT(i,j)^2/sum(subT(i,:),2)/sum(subT(:,j),1));
                    %Ulanowicz Ascendency
                    A = A +
subT(i,j)*log2(subT(i,j)*TST/sum(subT(i,:),2)/sum(subT(:,j),1));

                %If flow is zero, metrics remain the same
                else
                    %Ulanowicz Capacity
                    C = C + 0;
                    %Ulanowicz Reserve
                    Phi = Phi  + 0;
                    %Ulanowicz Ascendency
                    A = A + 0;
                end %end if statement
            end %end loop through columns
        end %end loop through rows

        %Ulanowicz metrics scaled to TST
        H = C/TST;
        Psi = Phi/TST;
        X = A/TST;

        %Add metrics to results matrix
        metrics_C(counter, l+1) = C;
        metrics_Phi(counter, l+1) = Phi;
        metrics_A(counter, l+1) = A;
        metrics_H(counter, l+1) = H;
        metrics_Psi(counter, l+1) = Psi;
        metrics_X(counter, l+1) = X;
    end %end loop through countries

    %increase counter
    counter = counter+1;

end %end loop through files
```

```
%Write metrics to a .csv file in the working directory
metricslist = {metrics_C, metrics_Phi, metrics_A, metrics_H, metrics_Psi,
metrics_X};
metricsnames = {'metrics_C', 'metrics_Phi', 'metrics_A', 'metrics_H',
'metrics_Psi', 'metrics_X'};
header = horzcat('Year',country);

for w=1:length(metricslist)

   metric = metricslist(w);
   metsort = sortrows(metric{1});
   metricsout = [header; num2cell(metsort)];
   numoutcols = size(metricsout,2);
   fname = sprintf('Domestic_%s.csv',metricsnames{w});
   fid = fopen(fname, 'w');
   headerrpt = repmat('%s,',1,numoutcols-1);
   metricrpt = repmat('%f,',1,numoutcols-1);
   fprintf(fid,[headerrpt,'%s\n'],metricsout{1,:});
   for q=2:size(metricsout,1)
       fprintf(fid,[metricrpt,'%f\n'],metricsout{q,:});
   end
   fclose(fid);
end
```

Domestic Closed Model

```
%Stephen Bond
%March 31 2015
%Domestic Metrics - Closed Model
%
%
%This code calculates Ulanowicz metrics for each country
%from WIOT Excel tables for each year. This version includes final use and
%value added

clear
clc

%Set working directory
%cd('/Users/StephenBond/Dropbox/Academic/Thesis/Workspace/International')
directory = uigetdir();
cd(directory);

%List all countries in WIOT files and set number of countries as a variable
country={'AUS','AUT','BEL','BGR','BRA','CAN','CHN','CYP','CZE','DEU','DNK',
'ESP','EST','FIN','FRA',...
'GBR','GRC','HUN','IDN','IND','IRL','ITA','JPN','KOR','LTU','LUX','LVA','MEX'
,'MLT','NLD','POL','PRT','ROU','RUS',...
'SVK','SVN','SWE','TUR','TWN','USA','RoW'};
countries = length(country);
```

```
%Loop through Excel files in directory and load into cell tables
files = dir('*.xlsx');

%Initialize counter
counter = 1;

%create results matrices for each metric
metrics_C = zeros(length(files), countries);
metrics_Phi = zeros(length(files), countries);
metrics_A = zeros(length(files), countries);
metrics_H = zeros(length(files), countries);
metrics_Psi = zeros(length(files), countries);
metrics_X = zeros(length(files), countries);

%loop through Excel files in directory and load into cell tables
for file = files'
    T = xlsread(file.name,'E7:BKF1448');
    %Get years for results output
    rawyear = file.name(5:6);
    numyear = str2num(rawyear);
    if numyear<50
        year = sprintf('20%s', rawyear);
    else
        year = sprintf('19%s', rawyear);
    end %end if statement for year assignment

    T(1436,:) = []; %Remove subtotal row to avoid double counting
    T(1439,:) = []; %Remove spending abroad row - sums to negative number

    %add WIOT year to first column of each results matrix
    metrics_C(counter,1) = str2num(year);
    metrics_Phi(counter,1) = str2num(year);
    metrics_A(counter,1) = str2num(year);
    metrics_H(counter,1) = str2num(year);
    metrics_Psi(counter,1) = str2num(year);
    metrics_X(counter,1) = str2num(year);

    %Loop through countries and define row and column boundaries for each
    for l = 1:countries
        %Loop through countries and set each capital formation and inventory
        %change column to 0. They will not be included in calculations, as
they
        %sum to negative values
        %formation = (l*4)+1435+(l-1);
        changes = (l*5)+1435;
        %T(:,formation)=[0];
        T(:,changes)=[0];
        %Create boundaries for country l's data, both intermediate and
        %final use
        domesticmin = (l-1)*35+1;
        domesticmax = l*35;
        finalmin = (l-1)*5+1436;
        finalmax = l*5+1435;
        %create matrices for intermediate and final use data
```

```
        finalT = T(domesticmin:domesticmax, finalmin:finalmax);
        domT = T(domesticmin:domesticmax, domesticmin:domesticmax);
        %add in Value Added data
        valTdom = T(1436:1440, domesticmin:domesticmax);
        valTfin = T(1436:1440, finalmin:finalmax);
        valTcat = horzcat(valTdom, valTfin);
        %concatenate into one matrix
        parT = horzcat(domT, finalT);
        subT = vertcat(parT, valTcat);
        numrows = size(subT,1);
        numcols = size(subT,2);
        TST = sum(sum(subT));

        %Set initial variable metrics to zero.
        C = 0;
        Phi = 0;
        A = 0;
        H = 0;
        Psi = 0;
        X = 0;

        %Loop through entires in WIOT table
        for i = 1:numrows
            for j = 1:numcols
                %Log(0)is not defined, so only calculate if flow is greater
                %than 0
                if subT(i,j)>0
                    %Ulanowicz Capacity
                    C = C - subT(i,j)*log2(subT(i,j)/TST);
                    %Ulanowicz Reserve
                    Phi = Phi -
subT(i,j)*log2(subT(i,j)^2/sum(subT(i,:),2)/sum(subT(:,j),1));
                    %Ulanowicz Ascendency
                    A = A +
subT(i,j)*log2(subT(i,j)*TST/sum(subT(i,:),2)/sum(subT(:,j),1));

                %If flow is zero, metrics remain the same
                else
                    %Ulanowicz Capacity
                    C = C + 0;
                    %Ulanowicz Reserve
                    Phi = Phi  + 0;
                    %Ulanowicz Ascendency
                    A = A + 0;
                end %end if statement
            end %end loop through columns
        end %end loop through rows

        %Ulanowicz metrics scaled to TST
        H = C/TST;
        Psi = Phi/TST;
        X = A/TST;

        %Add metrics to results matrix
        metrics_C(counter, l+1) = C;
        metrics_Phi(counter, l+1) = Phi;
```

```
        metrics_A(counter, l+1) = A;
        metrics_H(counter, l+1) = H;
        metrics_Psi(counter, l+1) = Psi;
        metrics_X(counter, l+1) = X;
    end %end loop through countries

    %increase counter
    counter = counter+1;

end %end loop through files

%Write metrics to a .csv file in the working directory
metricslist = {metrics_C, metrics_Phi, metrics_A, metrics_H, metrics_Psi,
metrics_X};
metricsnames = {'metrics_C', 'metrics_Phi', 'metrics_A', 'metrics_H',
'metrics_Psi', 'metrics_X'};
header = horzcat('Year',country);

for w=1:length(metricslist)

   metric = metricslist(w);
   metsort = sortrows(metric{1});
   metricsout = [header; num2cell(metsort)];
   numoutcols = size(metricsout,2);
   fname = sprintf('DomesticClosed_%s.csv',metricsnames{w});
   fid = fopen(fname, 'w');
   headerrpt = repmat('%s,',1,numoutcols-1);
   metricrpt = repmat('%f,',1,numoutcols-1);
   fprintf(fid,[headerrpt,'%s\n'],metricsout{1,:});
   for q=2:size(metricsout,1)
       fprintf(fid,[metricrpt,'%f\n'],metricsout{q,:});
   end
   fclose(fid);
end
```

Domestic Input-Output Model

```
%Stephen Bond
%April 22 2015
%Domestic Metrics - Input Output Model
%
%
%This script calculates Ulanowicz metrics for the domestic case,
%treating value added as inputs and final demand as outputs.
%Extracts data from WIOT Excel tables for each year and calulates for
%each country

clear
clc

%Set working directory
```

```matlab
%cd('/Users/StephenBond/Dropbox/Academic/Thesis/Workspace/International')
directory = uigetdir();
cd(directory);

%List all countries in WIOT files and set number of countries as a variable
country={'AUS','AUT','BEL','BGR','BRA','CAN','CHN','CYP','CZE','DEU',...
    'DNK','ESP','EST','FIN','FRA','GBR','GRC','HUN','IDN','IND','IRL',...
    'ITA','JPN','KOR','LTU','LUX','LVA','MEX','MLT','NLD','POL','PRT',...
    'ROU','RUS','SVK','SVN','SWE','TUR','TWN','USA','RoW'};
countries = length(country);

%Loop through Excel files in directory and load into cell tables
files = dir('*.xlsx');

%Initialize counter
counter = 1;

%create results matrices for each metric
metrics_C = zeros(length(files), countries);
metrics_Phi = zeros(length(files), countries);
metrics_A = zeros(length(files), countries);
metrics_H = zeros(length(files), countries);
metrics_Psi = zeros(length(files), countries);
metrics_X = zeros(length(files), countries);

%loop through Excel files in directory and load into cell tables
for file = files'
    %Read all values into matrix
    TT = xlsread(file.name,'E7:BKF1448');
    TT(1436, :)=[];

    %Get years for results output
    rawyear = file.name(5:6);
    numyear = str2num(rawyear);
    if numyear<50
        year = sprintf('20%s', rawyear);
    else
        year = sprintf('19%s', rawyear);
    end %end if statement for year assignment

    %add WIOT year to first column of each results matrix
    metrics_C(counter,1) = str2num(year);
    metrics_Phi(counter,1) = str2num(year);
    metrics_A(counter,1) = str2num(year);
    metrics_H(counter,1) = str2num(year);
    metrics_Psi(counter,1) = str2num(year);
    metrics_X(counter,1) = str2num(year);

    %Loop through countries and define row and column boundaries for each
    for l = 1:countries
        domesticmin = (l-1)*35+1;
        domesticmax = l*35;

        O_raw = TT(domesticmin:domesticmax,:);
        I_raw = TT(:, domesticmin:domesticmax);
```

```
O_raw(:, domesticmin:domesticmax)=[];
I_raw(domesticmin:domesticmax,:)=[];

%collapse input and output matrices into vectors of sums
I = sum(I_raw, 1);
O = sum(O_raw, 2);

%Handle negatives in input by zeroing out negative and
%adding it's opposite to relevant output
for p = 1:length(I)
    if I(p) < 0
        O(p) = O(p)+abs(I(p));
        I(p) = 0;
    else
        I(p) = I(p);
    end
end

%Handle negatives in output by zeroing out negative and
%adding it's opposite to relevant input
for q = 1:length(O)
    if O(q) < 0
        I(q) = I(q)+abs(O(q));
        O(q) = 0;
    else
        O(q) = O(q);
    end
end

%create matrix with only domestic flows and corresponding I/O
subTT = TT(domesticmin:domesticmax, domesticmin:domesticmax);
subT = [subTT O;
    I 0];

%Runs through only intermediate flows, but uses all for TST
numrows = size(subTT,1);
numcols = size(subTT,2);
TST = sum(sum(subTT)) + sum(I);

%Set initial variable metrics to zero.
C = 0;
Phi = 0;
A = 0;
H = 0;
Psi = 0;
X = 0;
OO = 0;


%Calculate open system add-on from inputs
for m = 1:length(I)
    if I(m) == 0
        OO = OO;
    else
        OO = OO-I(m)*log2(I(m)/(I(m)+sum(subTT(:,m))));
```

```
            end
        end

        %Calculate open system add-on from outputs
        for n = 1:length(O)
            if O(n) == 0
                OO = OO;
            else
                OO = OO-O(n)*log2(O(n)/(O(n)+sum(subTT(n,:))));
            end
        end

        %Loop through entires in WIOT table
        for i = 1:numrows
            for j = 1:numcols
                %Log(0)is not defined, so only calculate if flow is greater
                %than 0
                if subT(i,j)>0
                    %Ulanowicz Capacity
                    C = C - subT(i,j)*log2(subT(i,j)/TST);
                    %Ulanowicz Reserve
                    Phi = Phi -
subT(i,j)*log2(subT(i,j)^2/sum(subT(i,:),2)/sum(subT(:,j),1));
                    %Ulanowicz Ascendency
                    A = A +
subT(i,j)*log2(subT(i,j)*TST/sum(subT(i,:),2)/sum(subT(:,j),1));

                %If flow is zero, metrics remain the same
                else
                    %Ulanowicz Capacity
                    C = C + 0;
                    %Ulanowicz Reserve
                    Phi = Phi  + 0;
                    %Ulanowicz Ascendency
                    A = A + 0;
                end %end if statement
            end %end loop through columns
        end %end loop through rows

        %Add open model corrections to metrics
        C = C + 2*OO;
        Phi = Phi + OO;
        A = A + OO;

        %Ulanowicz metrics scaled to TST
        H = C/TST;
        Psi = Phi/TST;
        X = A/TST;

        %Add metrics to results matrix
        metrics_C(counter, l+1) = C;
        metrics_Phi(counter, l+1) = Phi;
        metrics_A(counter, l+1) = A;
        metrics_H(counter, l+1) = H;
        metrics_Psi(counter, l+1) = Psi;
        metrics_X(counter, l+1) = X;
```

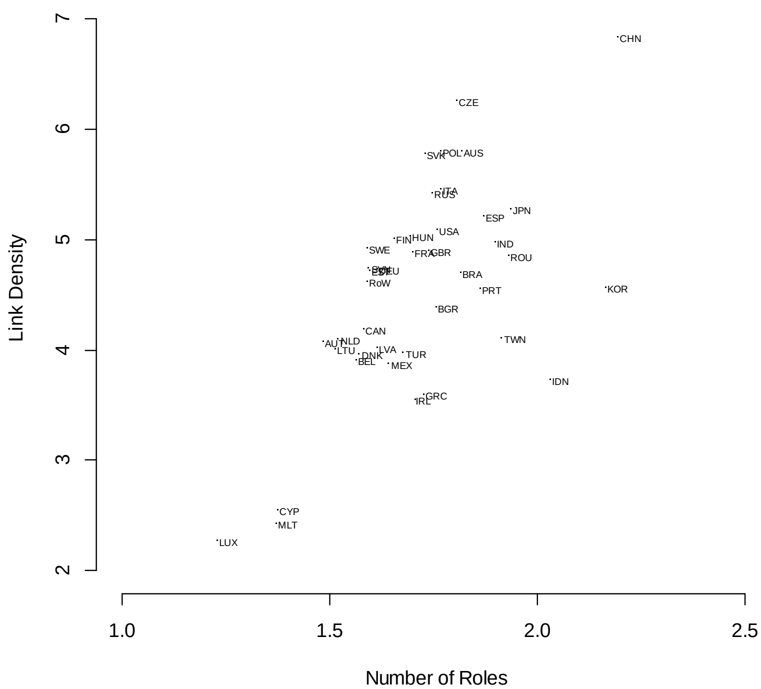
```
    end %end loop through countries

    %increase counter
    counter = counter+1;

end %end loop through files

%Write metrics to a .csv file in the working directory
metricslist = {metrics_C, metrics_Phi, metrics_A, metrics_H, metrics_Psi,
metrics_X};
metricsnames = {'metrics_C', 'metrics_Phi', 'metrics_A', 'metrics_H',
'metrics_Psi', 'metrics_X'};
header = horzcat('Year',country);

for w=1:length(metricslist)

   metric = metricslist(w);
   metsort = sortrows(metric{1});
   metricsout = [header; num2cell(metsort)];
   numoutcols = size(metricsout,2);
   fname = sprintf('Domestic_IO_%s.csv',metricsnames{w});
   fid = fopen(fname, 'w');
   headerrpt = repmat('%s,',1,numoutcols-1);
   metricrpt = repmat('%f,',1,numoutcols-1);
   fprintf(fid,[headerrpt,'%s\n'],metricsout{1,:});
   for q=2:size(metricsout,1)
       fprintf(fid,[metricrpt,'%f\n'],metricsout{q,:});
   end
   fclose(fid);
end
```

APPENDIX C: ADDITIONAL PLOTS

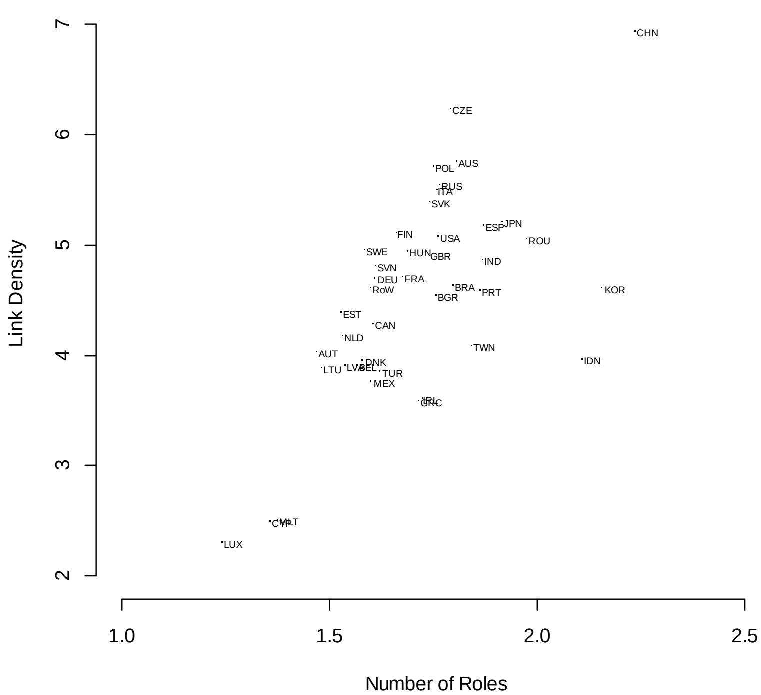
The plots included below are scatter plots of effective connectivity (m) vs. number of roles (n), similar to those in Figures 63, 64, and 6, but representing individual years or countries. Plots for metrics calculated by closed and input-output models are included.

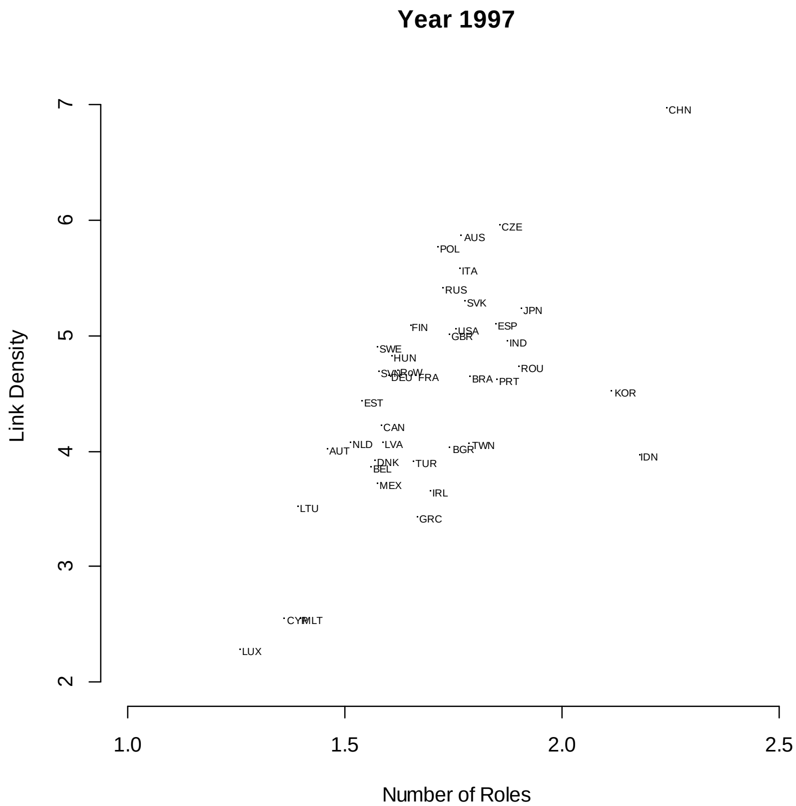
All Countries by Year – Input-Output Model

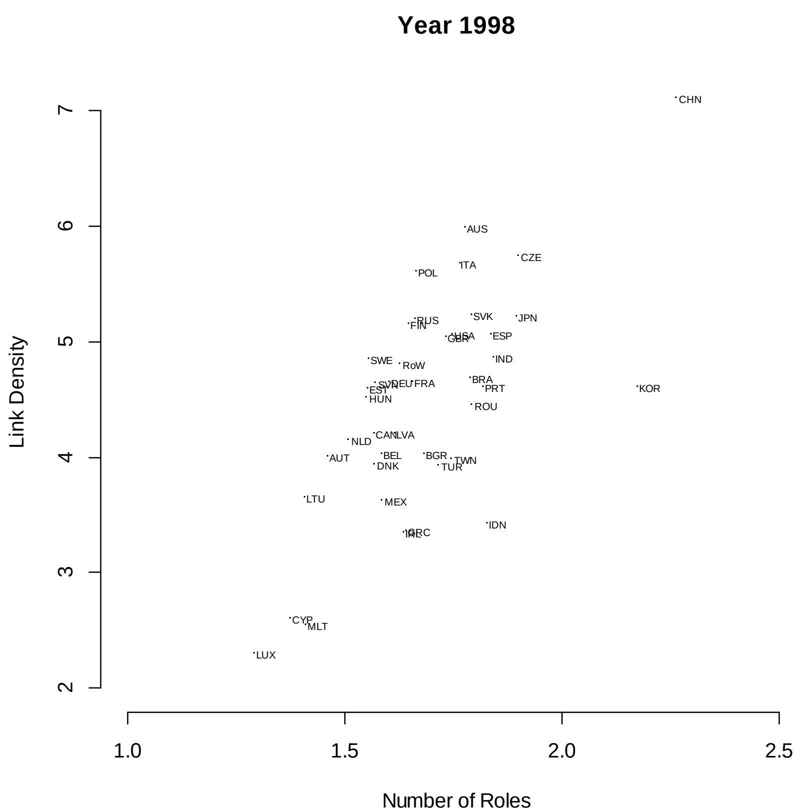
Year 1995

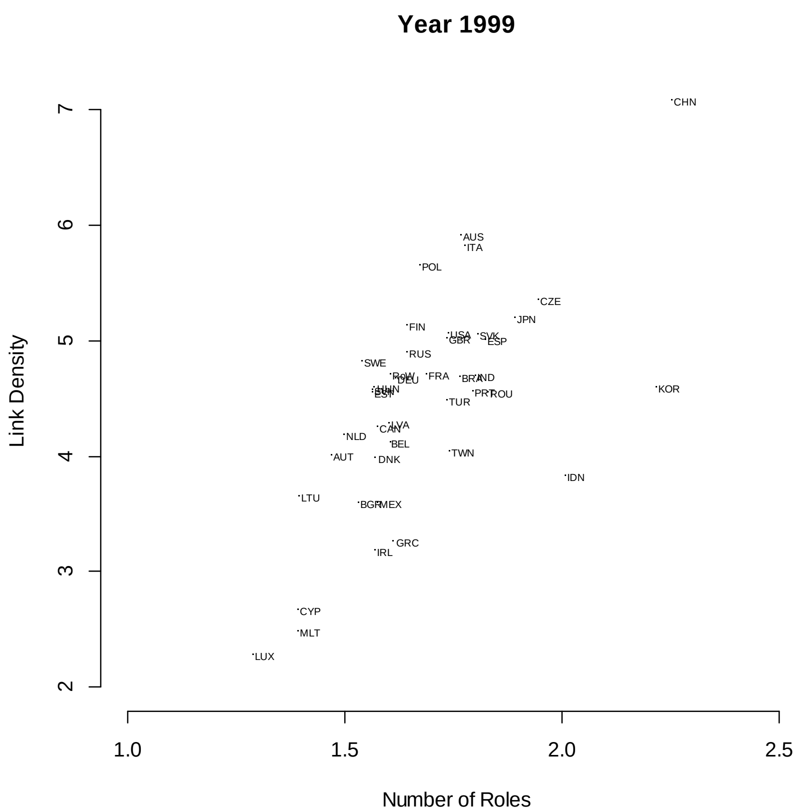


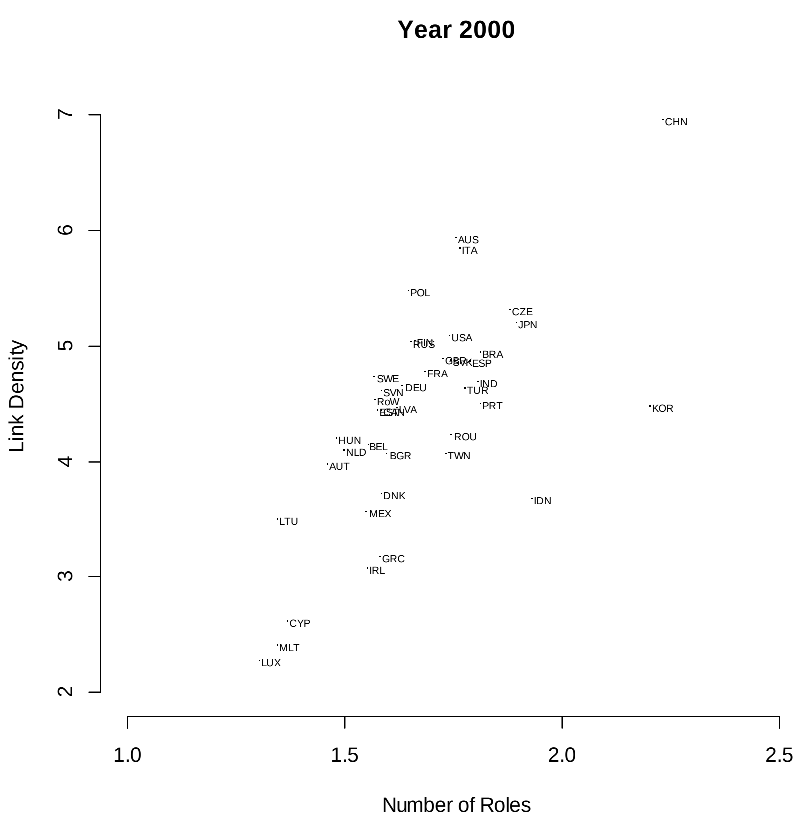
Year 1996



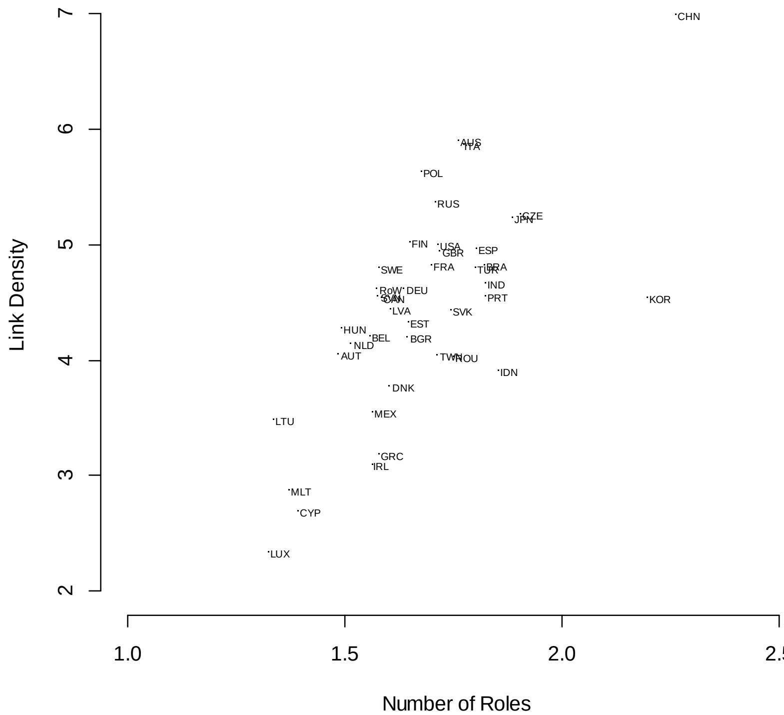

Year 1997
Link Density
Number of Roles
CHN
CZE
AUS
POL
ITA
RUS
SVK
JPN
FIN
USA
GBR
ESP
IND
SWE
HUN
ROU
DEU
FRA
BRA
PRT
KOR
EST
CAN
NLD
LVA
AUT
BGR
TWN
IDN
DNK
BEL
TUR
MEX
IRL
LTU
GRC
MLT
LUX


Year 1998
Link Density
Number of Roles
CHN
AUS
CZE
ITA
POL
SVK
JPN
RUS
FIN
USA
GBR
ESP
IND
SWE
RoW
BRA
FRA
PRT
KOR
EST
HUN
ROU
LVA
NLD
BEL
BGR
TWN
AUT
DNK
TUR
LTU
MEX
IDN
CYP
MLT
LUX

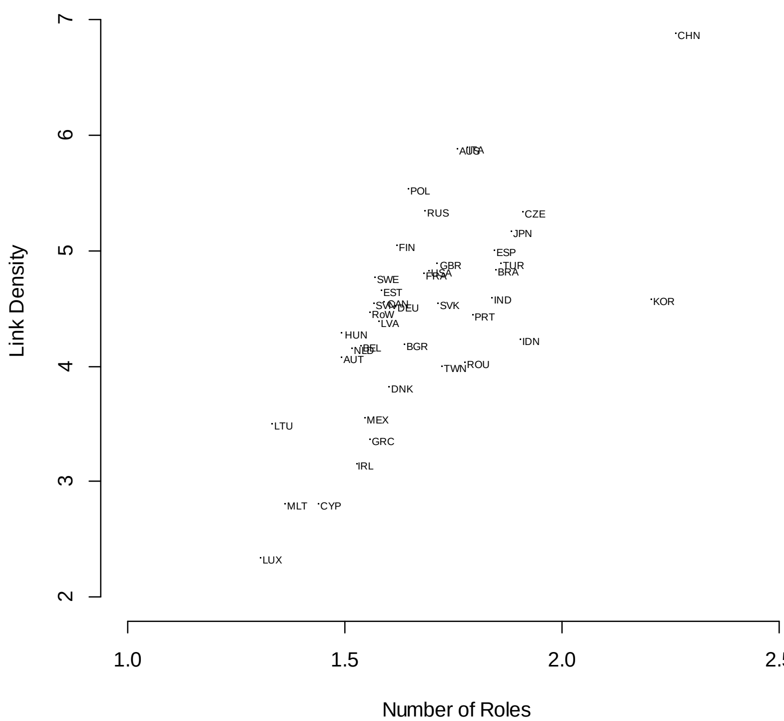

Year 1999
Link Density
Number of Roles
CHN
AUS
ITA
POL
CZE
JPN
FIN
USA
GBR
SVK
ESP
RUS
SWE
FRA
BRA
IND
DEU
HUN
PRT
ROU
KOR
TUR
LVA
NLD
BEL
AUT
DNK
TWN
IDN
LTU
BGR
MEX
GRC
IRL
CYP
MLT
LUX

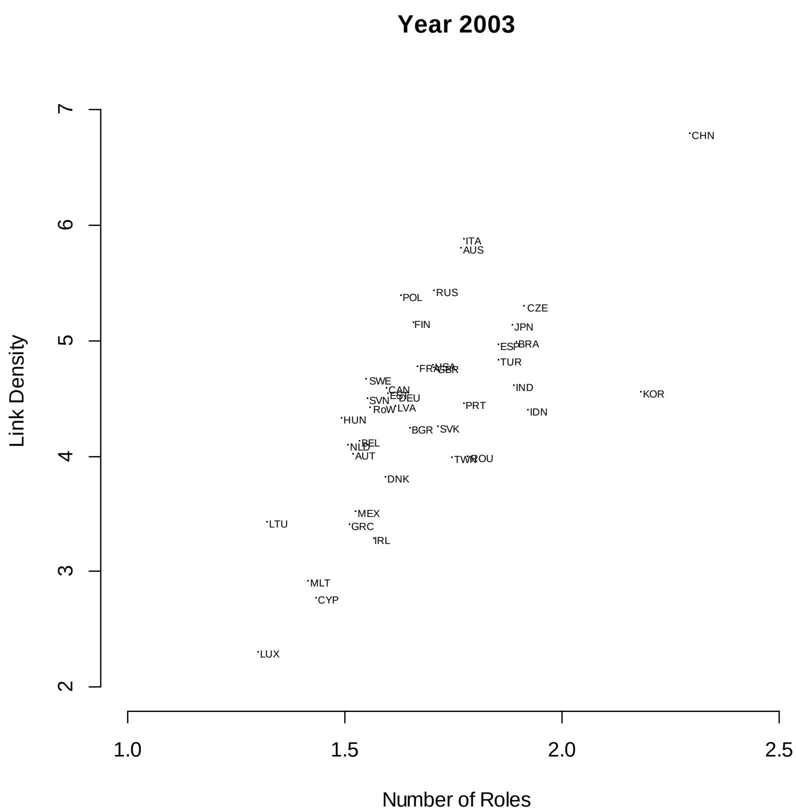

Year 2000
Link Density
Number of Roles
CHN
AUS
ITA
POL
CZE
JPN
USA
RUS
BRA
GBR
ESP
FRA
SWE
DEU
IND
SVN
TUR
RoW
LVA
PRT
KOR
ROU
HUN
BEL
NLD
BGR
TWN
AUT
DNK
IDN
MEX
LTU
GRC
IRL
CYP
MLT
LUX

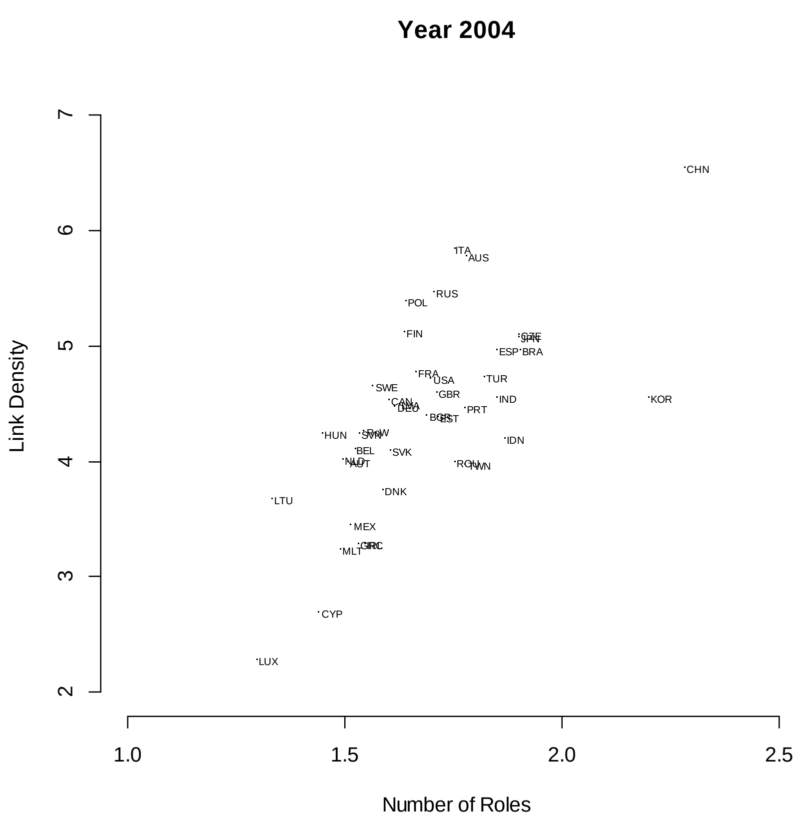
Year 2001



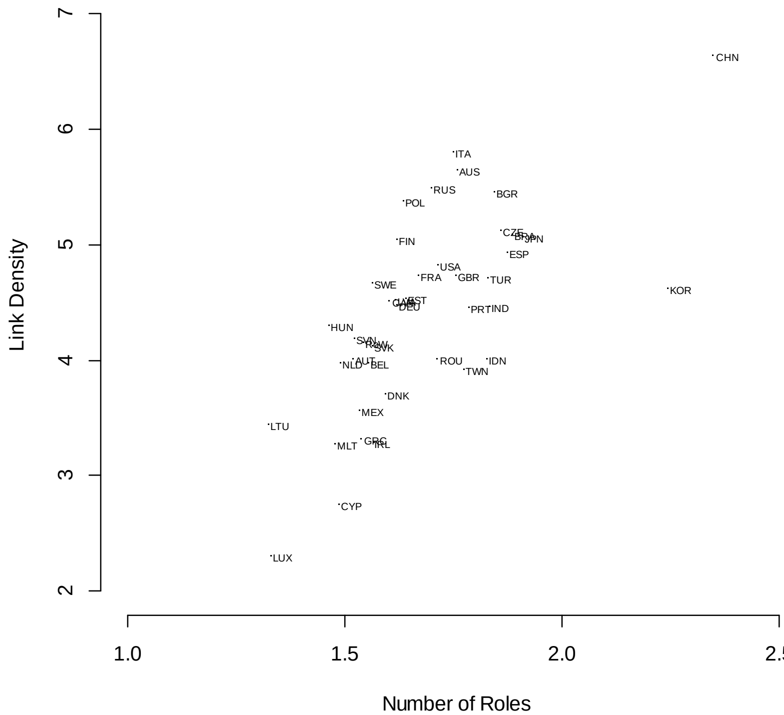
Year 2002



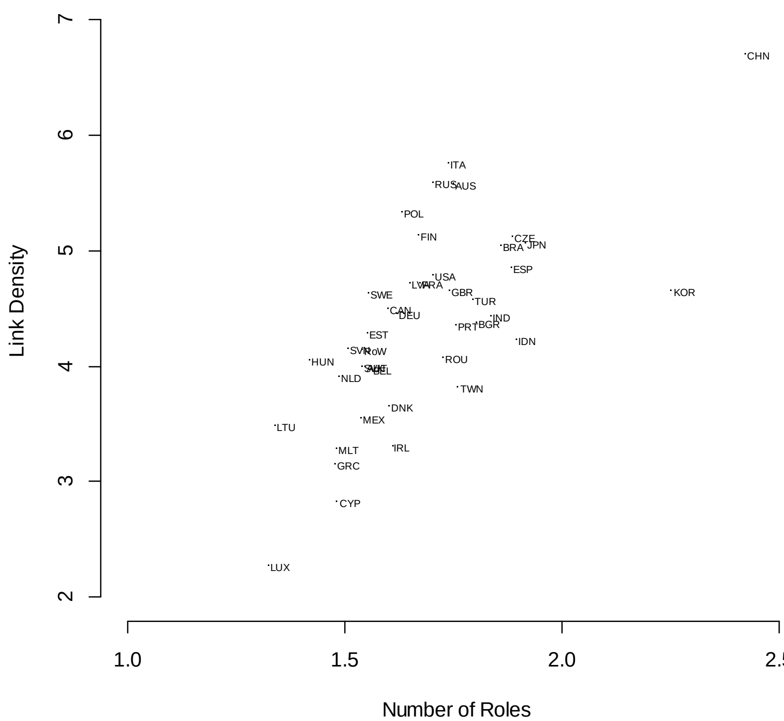

Year 2003
Link Density
Number of Roles
2
3
4
5
6
7
1.0
1.5
2.0
2.5
CHN
ITA
AUS
POL
RUS
CZE
FIN
JPN
ESP
BRA
TUR
FRA
USA
GBR
SWE
CAN
DEU
SVN
RoW
LVA
IND
KOR
PRT
IDN
HUN
BGR
SVK
BEL
NLD
AUT
TWN
ROU
DNK
MEX
LTU
GRC
IRL
MLT
CYP
LUX


Year 2004
Link Density
Number of Roles
2
3
4
5
6
7
1.0
1.5
2.0
2.5
CHN
ITA
AUS
RUS
POL
FIN
CZE
JPN
ESP
BRA
FRA
USA
TUR
SWE
GBR
IND
KOR
CAN
DEU
PRT
BGR
EST
HUN
SVN
RoW
IDN
BEL
SVK
NLD
AUT
ROU
TWN
DNK
LTU
MEX
MLT
CYP
LUX

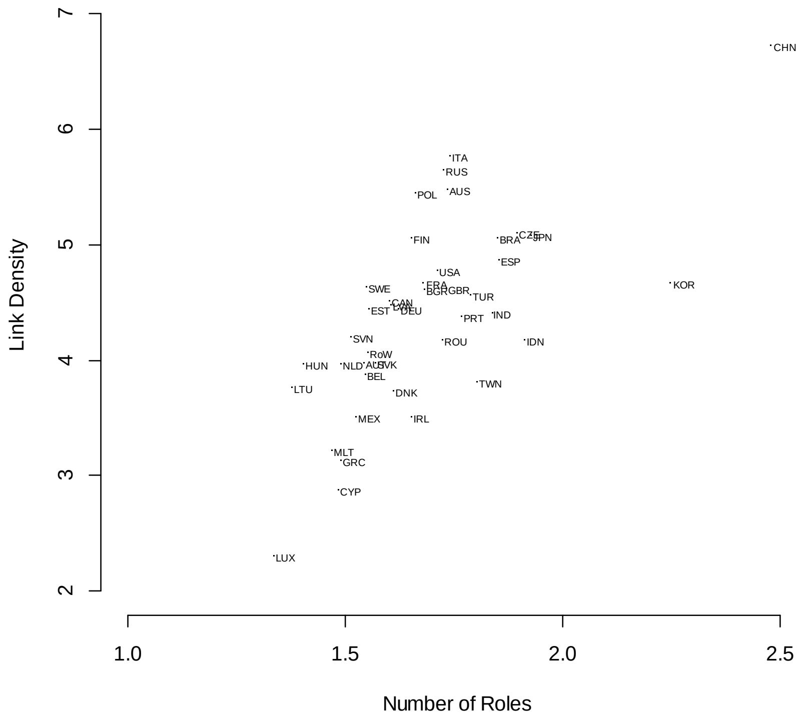
Year 2005



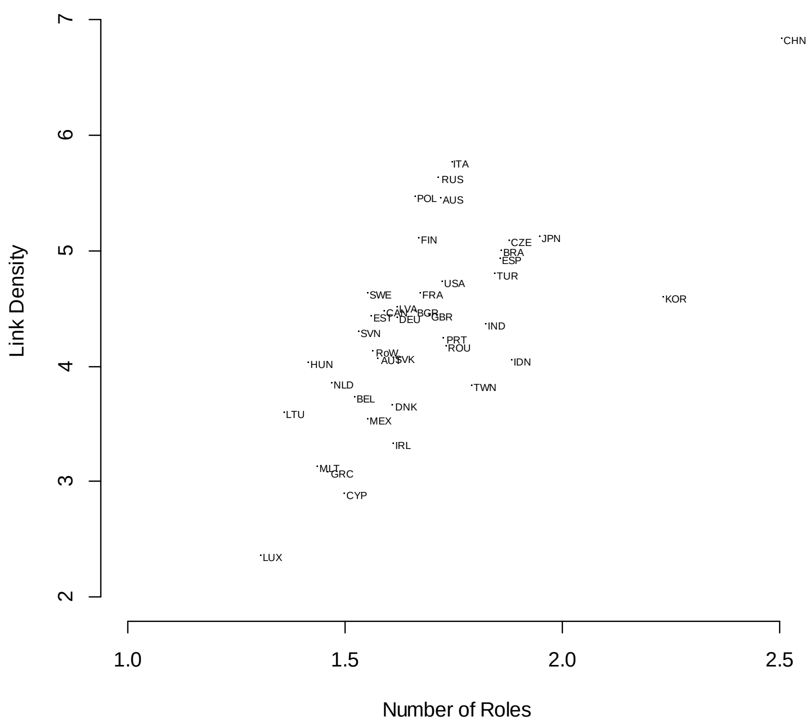
Year 2006



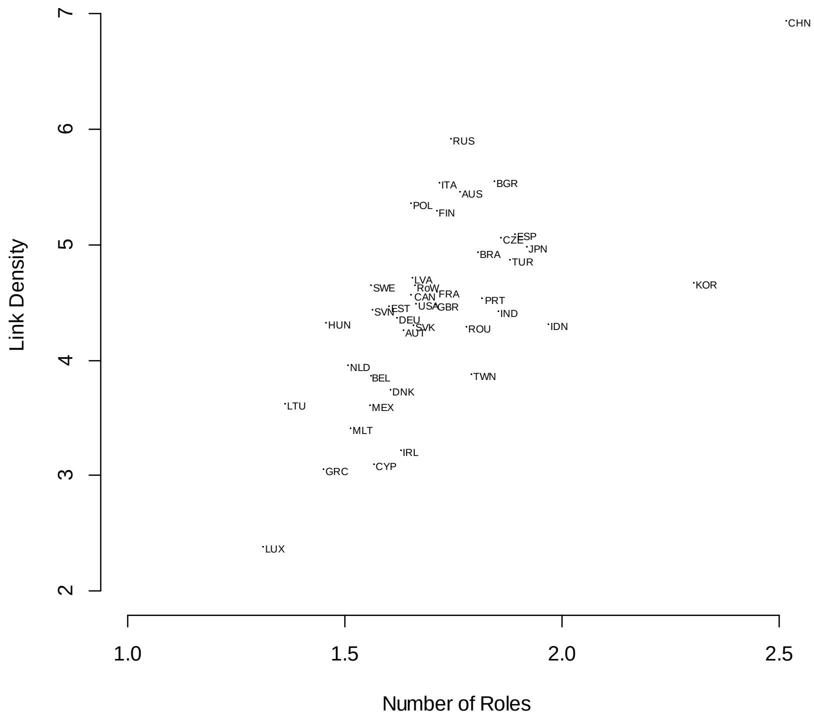
Year 2007



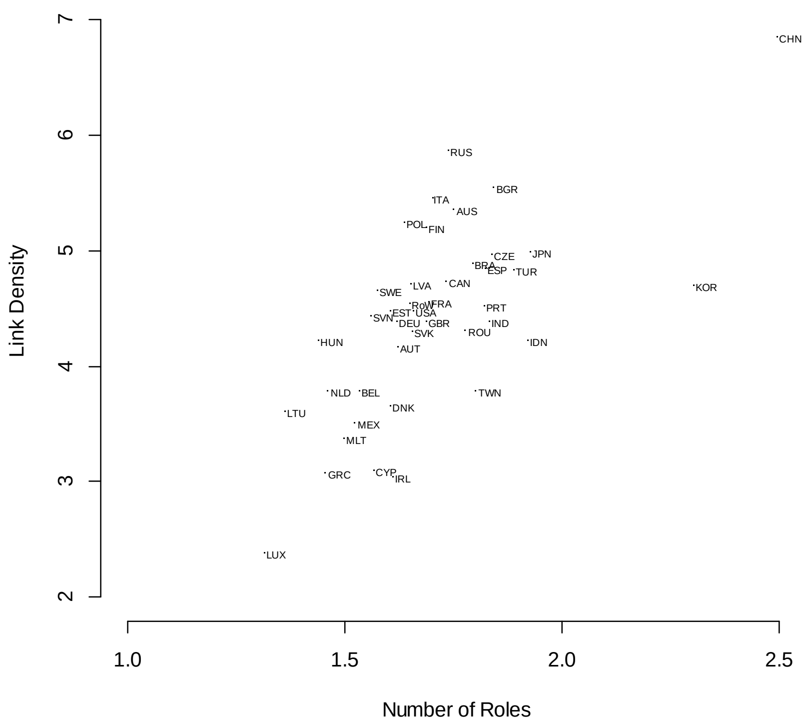
Year 2008

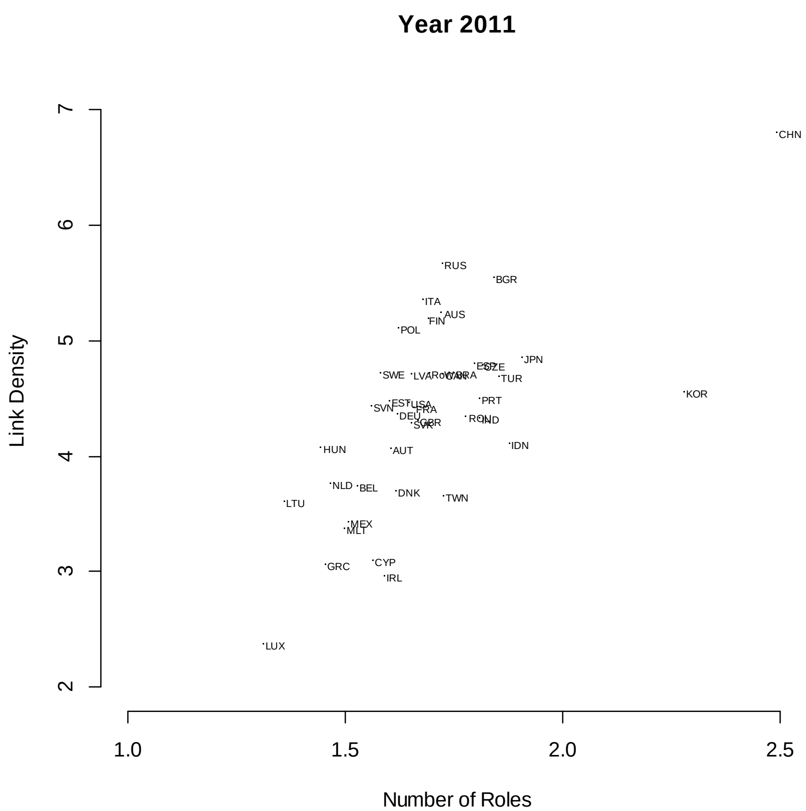


Year 2009



Year 2010





Year 2011
Link Density
Number of Roles
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2.0
2.5
2
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6
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CHN
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BGR
ITA
AUS
FIN
POL
JPN
SWE
TUR
KOR
PRT
SVN
IDN
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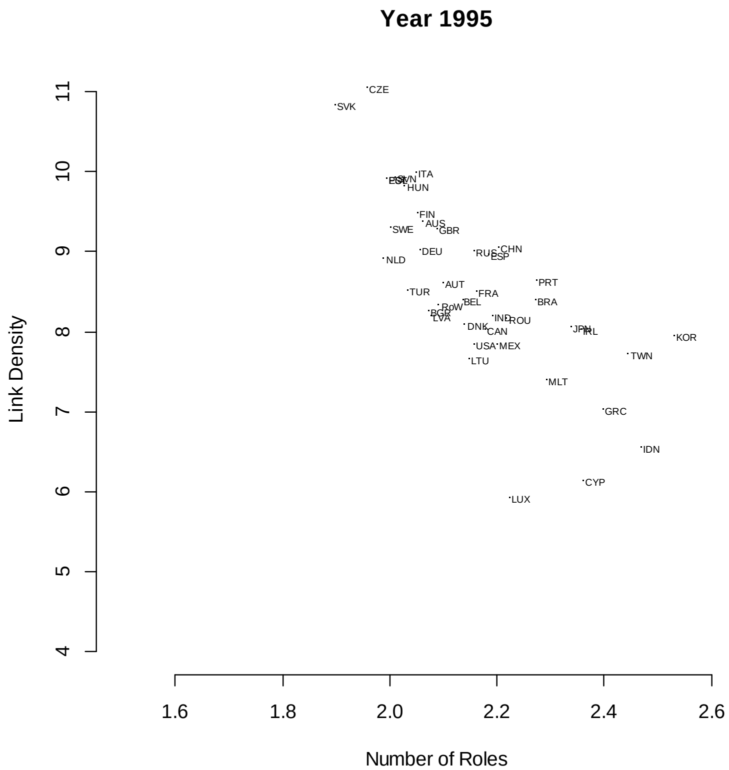
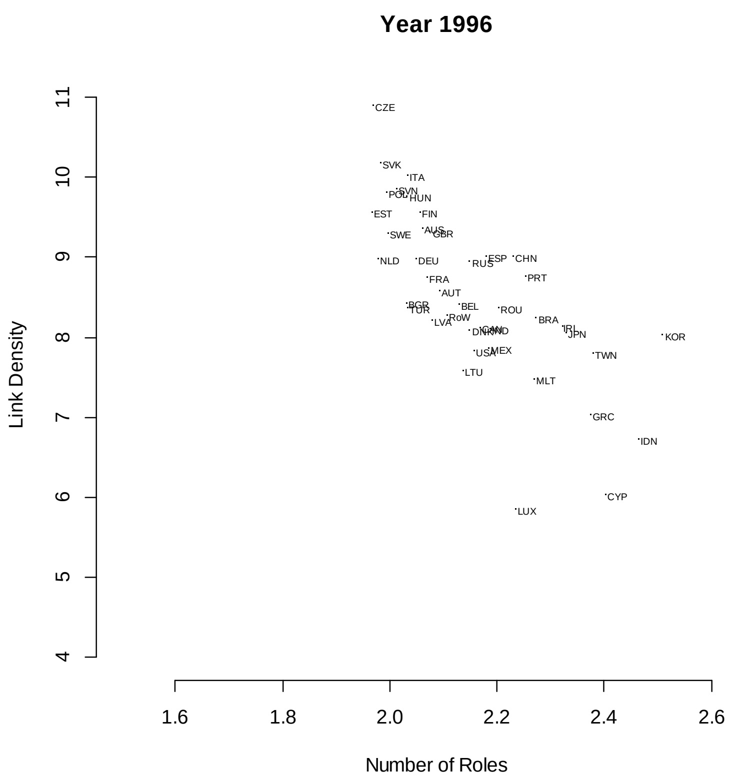
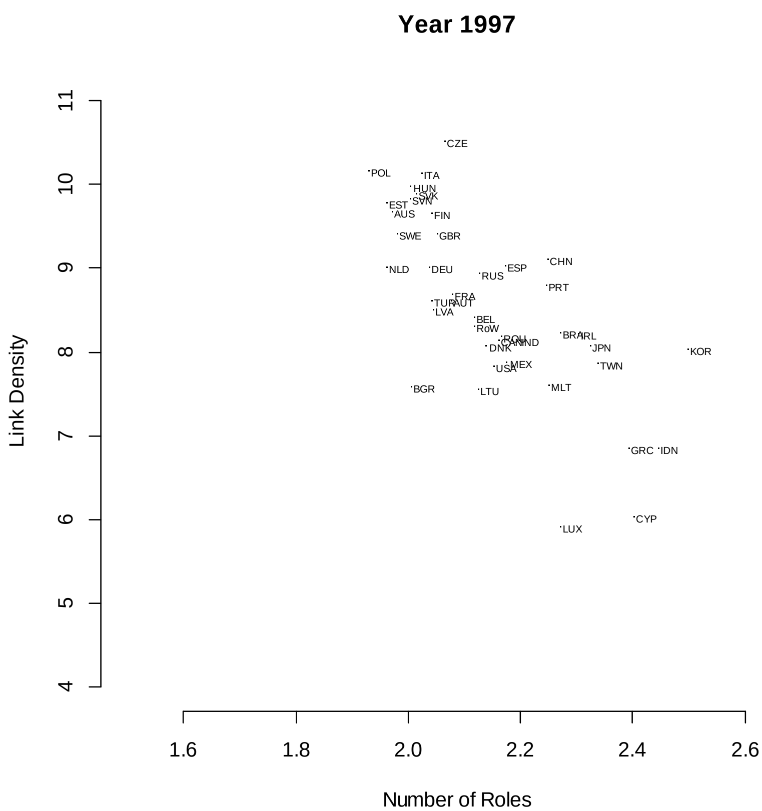
MEX
MLT
CYP
GRC
IRL
LUX

All Countries by Year – Closed Model



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RUS
PRT
FRA
TUR
AUT
LVA
BEL
RoW
BRA
IRL
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KOR
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TWN
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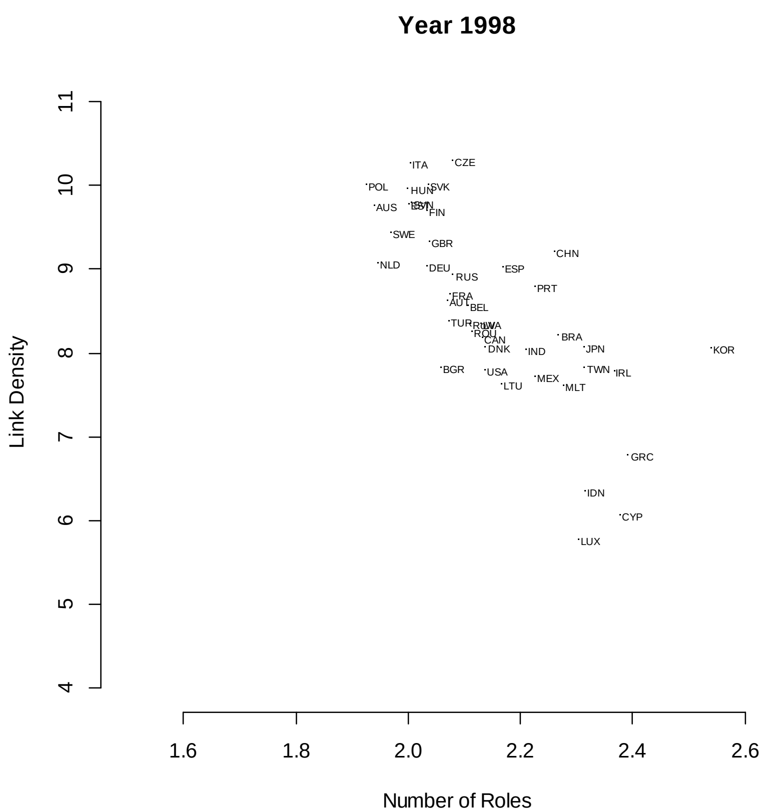
LTU
MLT
GRC
IDN
CYP
LUX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SWE
GBR
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LVA
ROU
CAN
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IRL
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LTU
MLT
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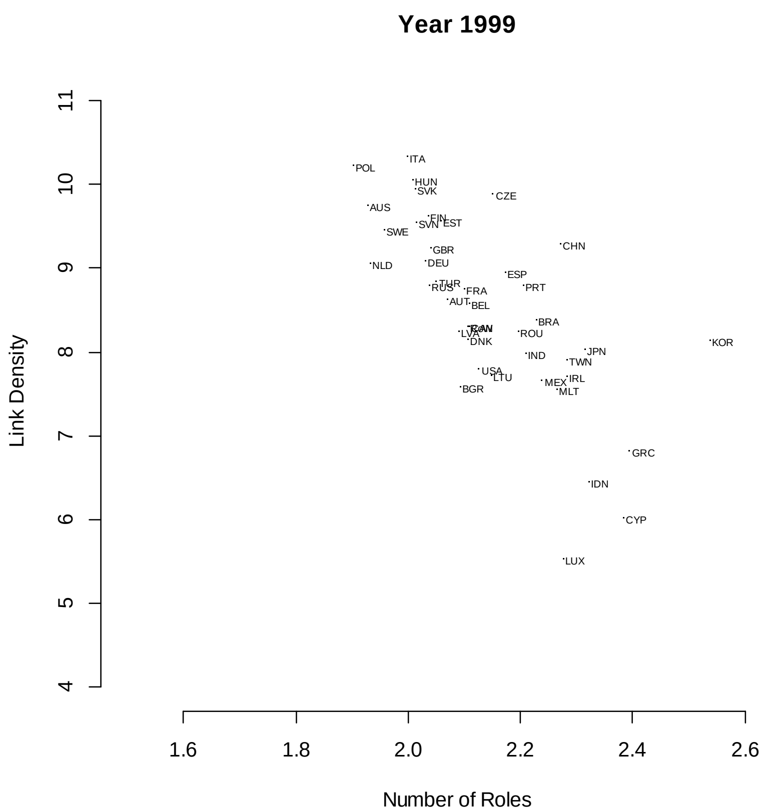
IDN
CYP
LUX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Link Density
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TUR
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PRT
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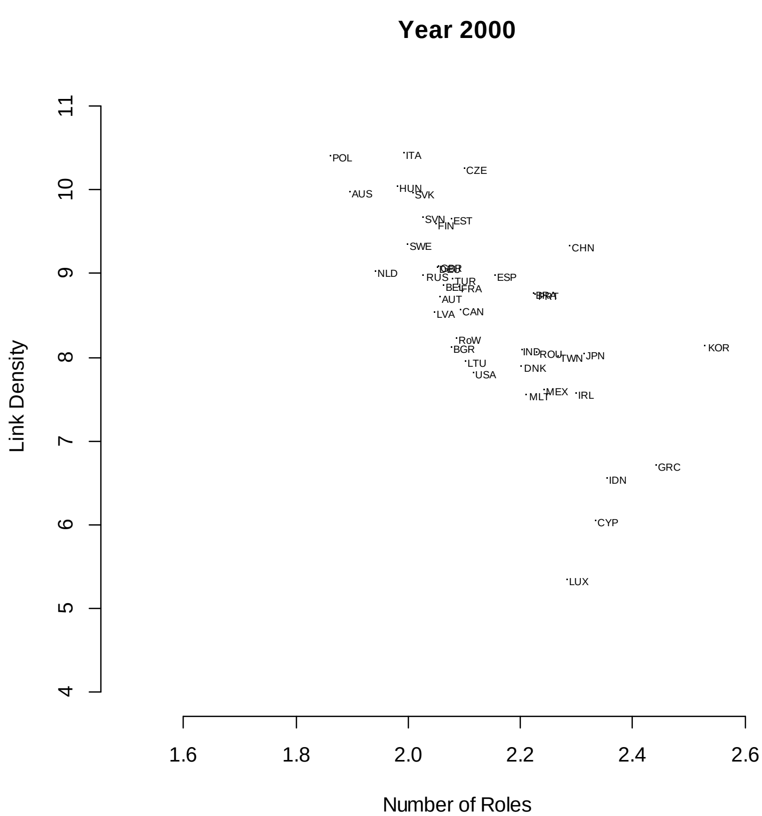
IDN
CYP
LUX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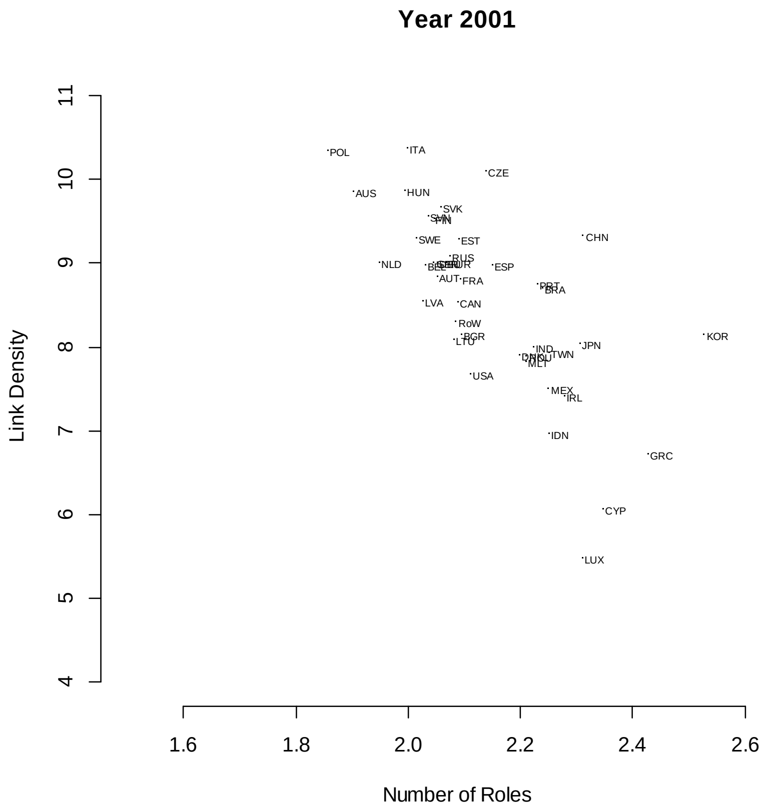
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POL
ITA
CZE
AUS
HUN
SVK
SWE
EST
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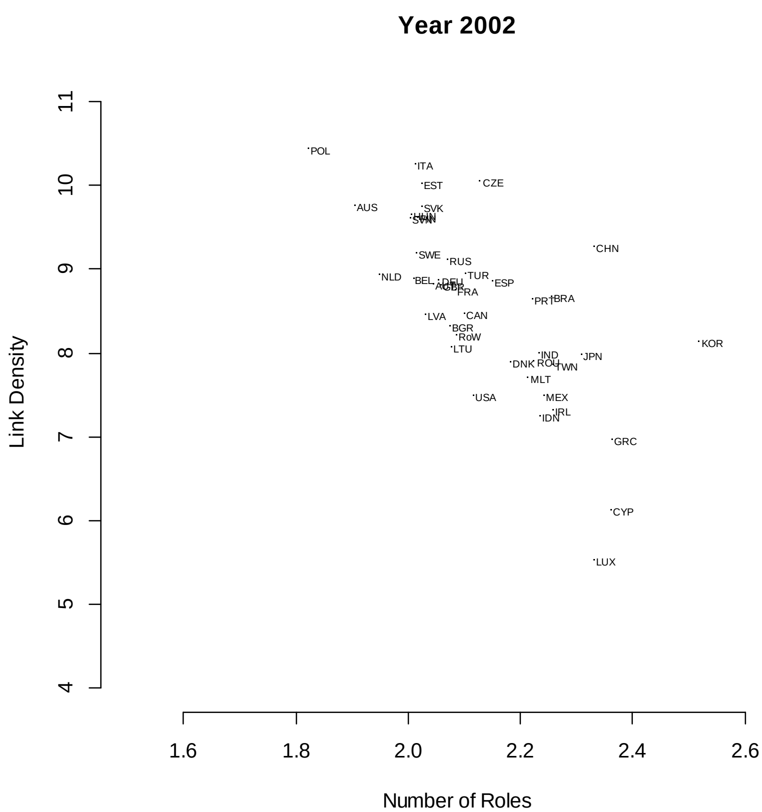
IDN
GRC
CYP
LUX


Year 2002
Link Density
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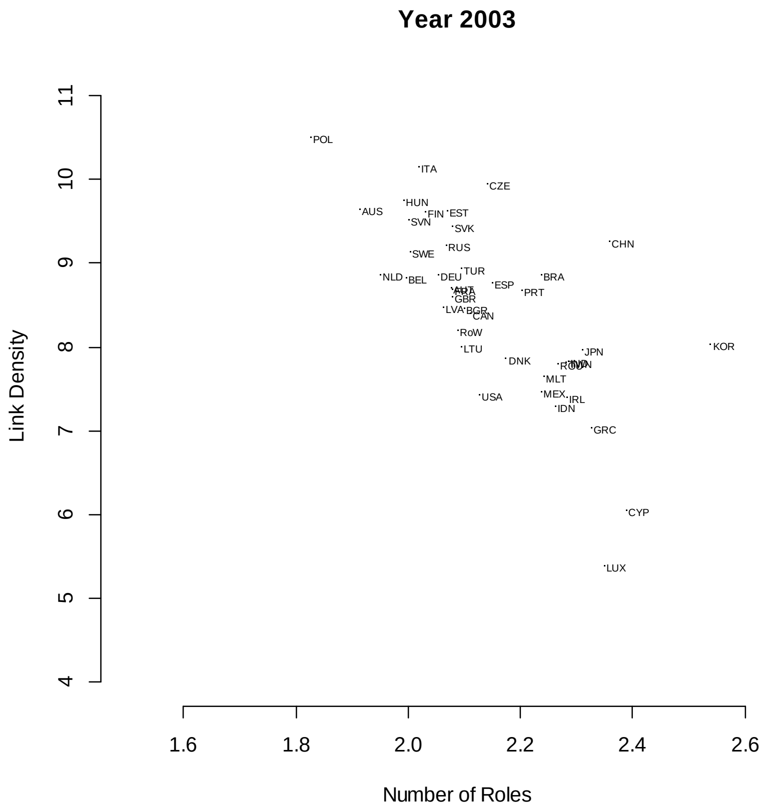
Year 2003
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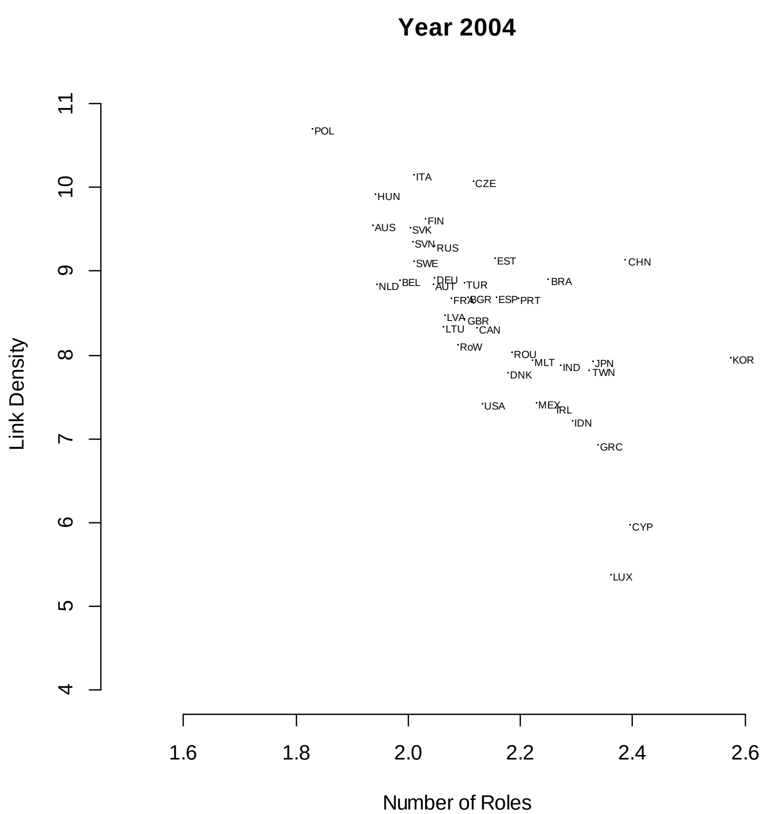
GRC
CYP
LUX


Year 2004
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GBR
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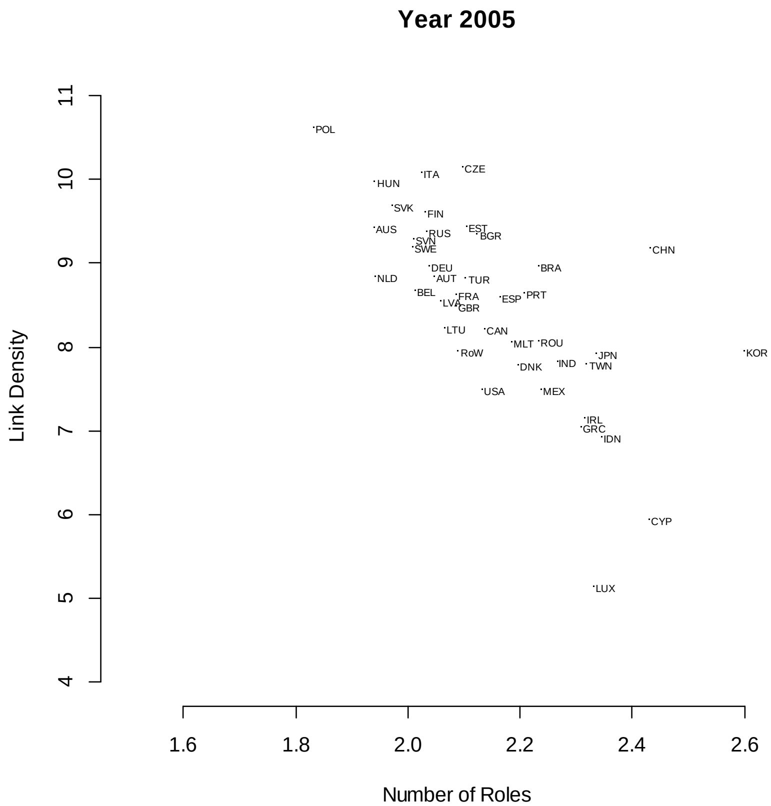
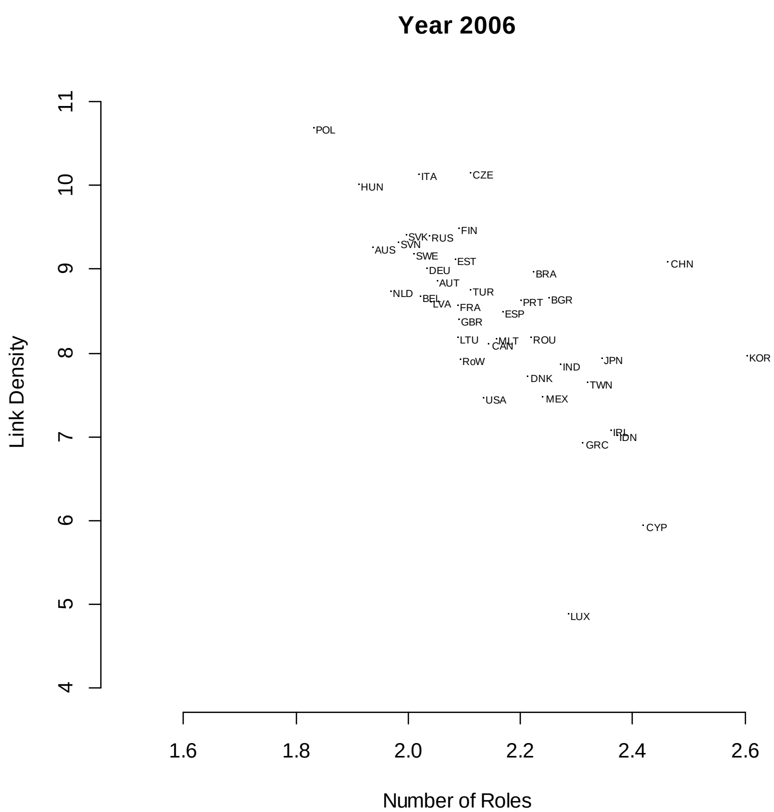


Year 2005
Link Density
Number of Roles



Year 2006
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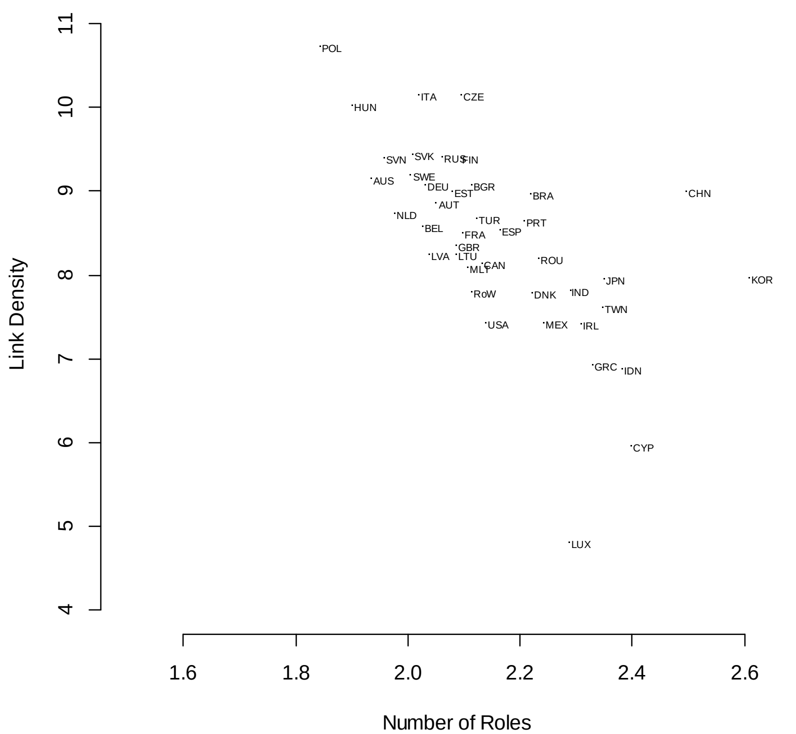
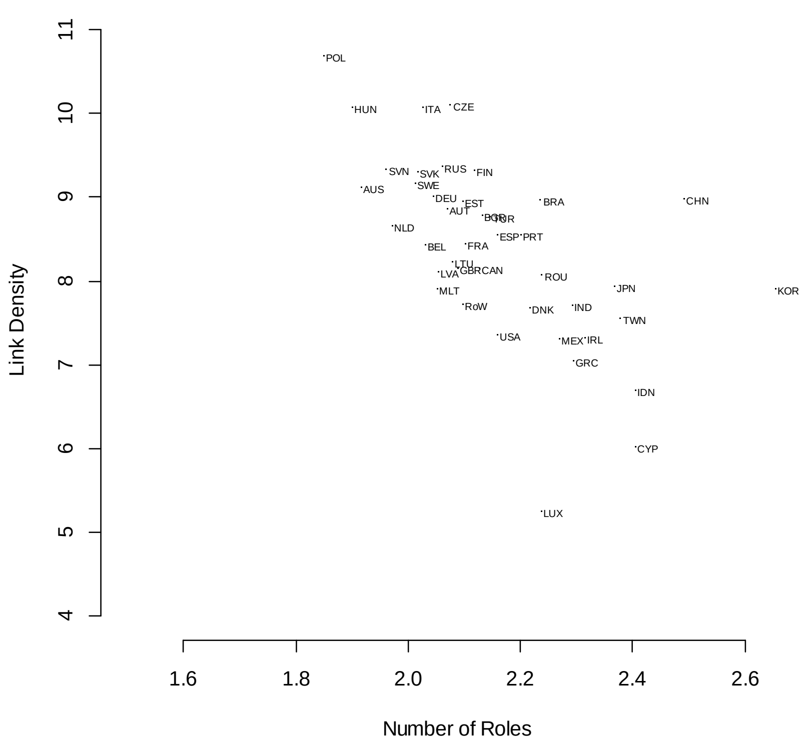
Number of Roles

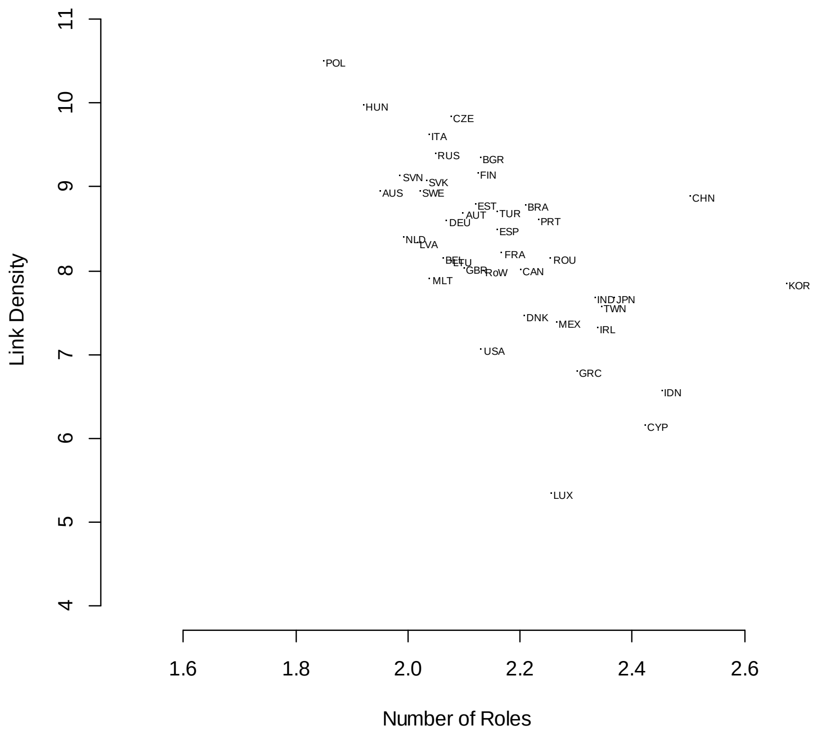
Year 2007



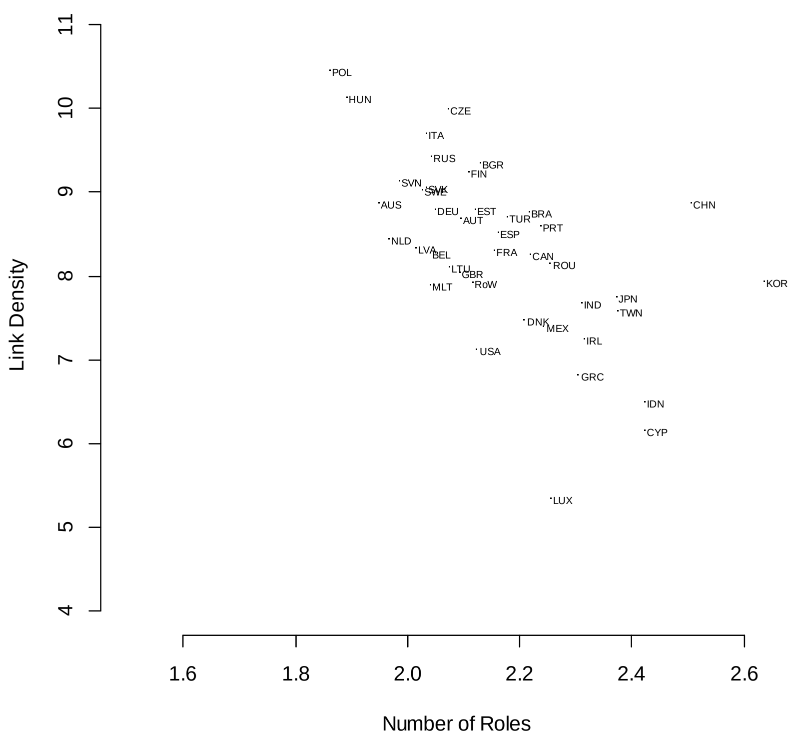
Year 2008

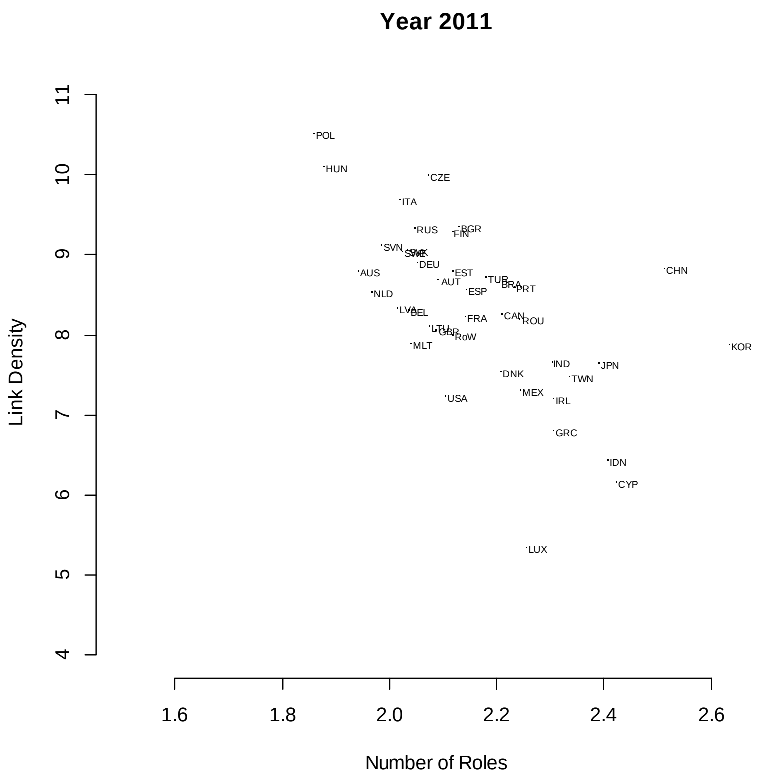


Year 2009



Year 2010




Year 2011
Link Density
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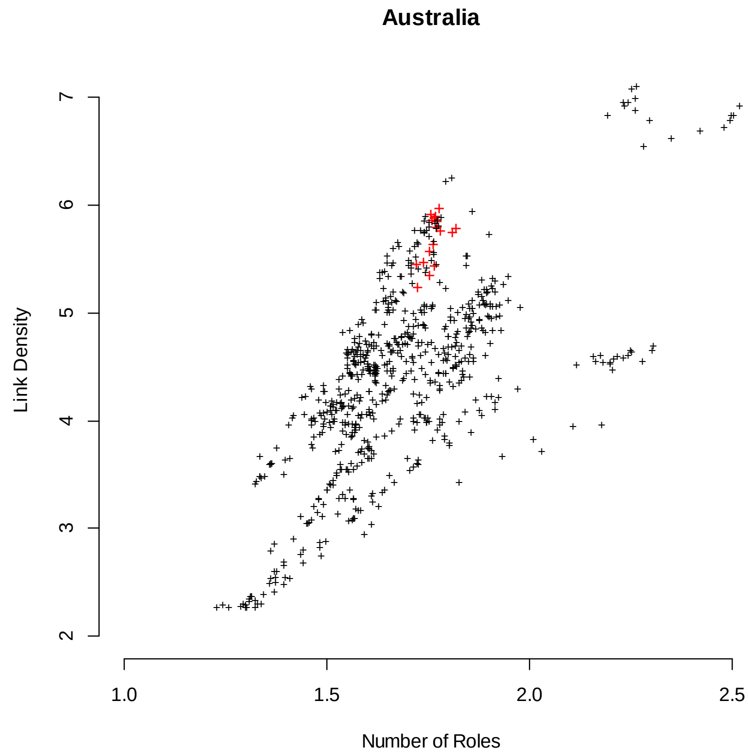
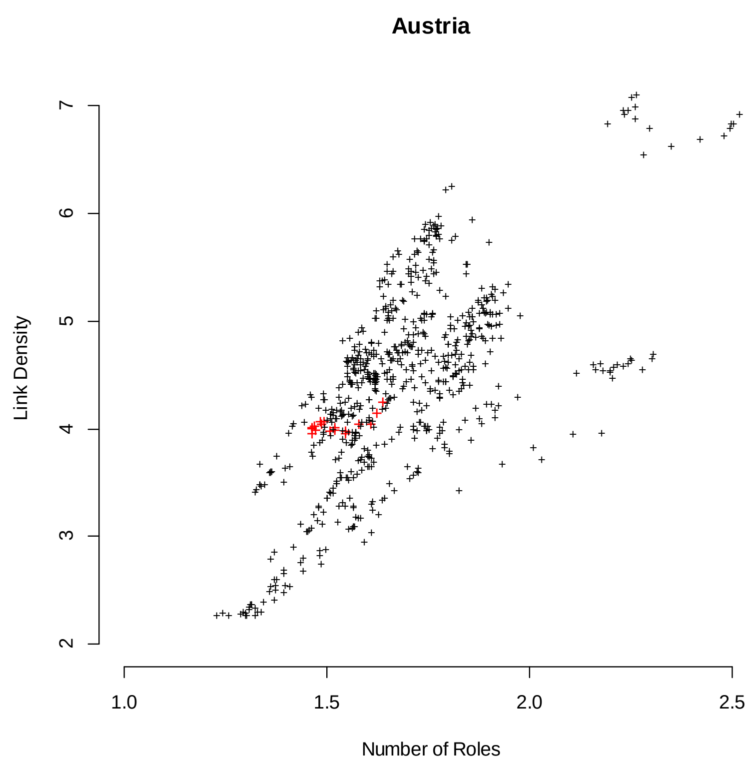
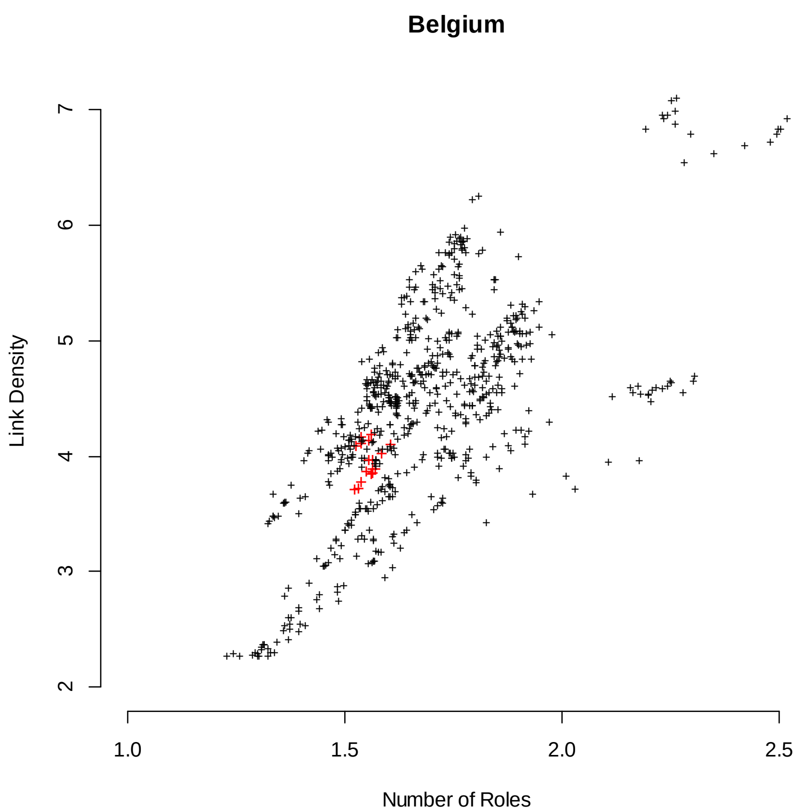
IRL
GRC
IDN
CYP
LUX

All Years, Individual Countries Highlighted – Input-Output Model



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Link Density
Number of Roles
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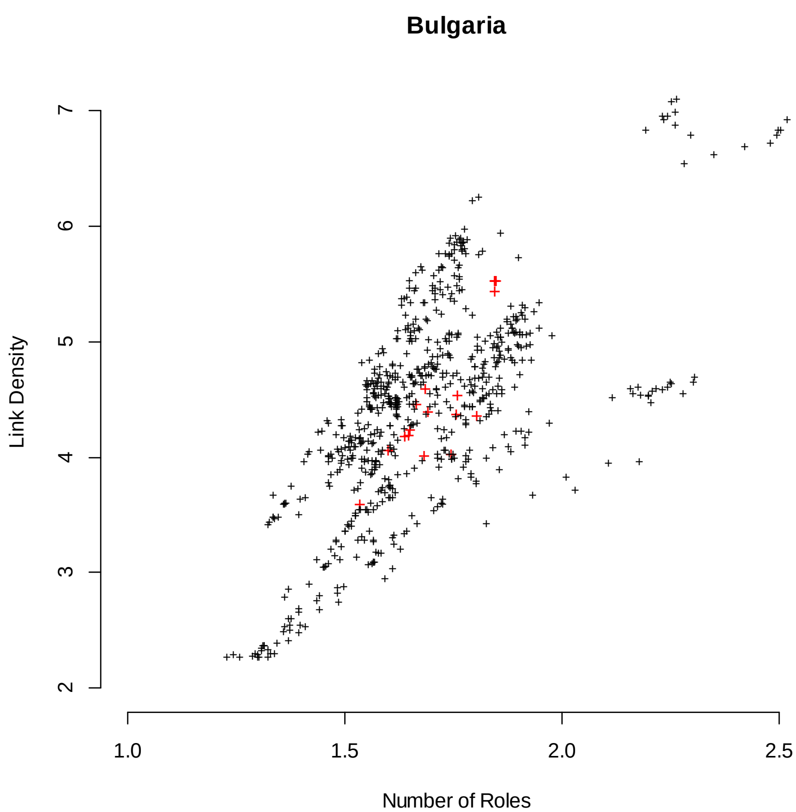
Bulgaria
Link Density
Number of Roles
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2.5
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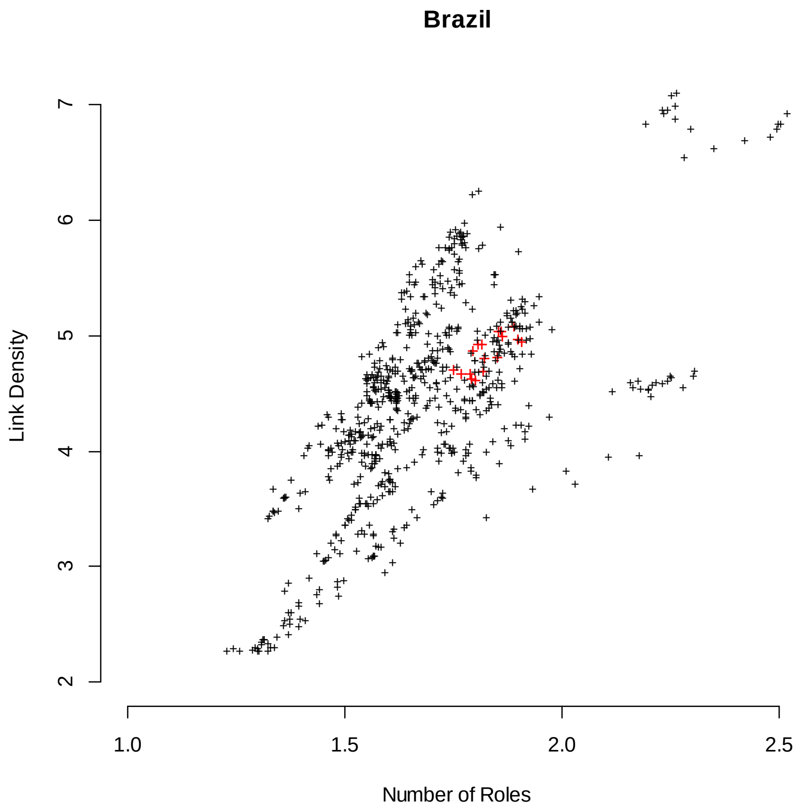
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Link Density
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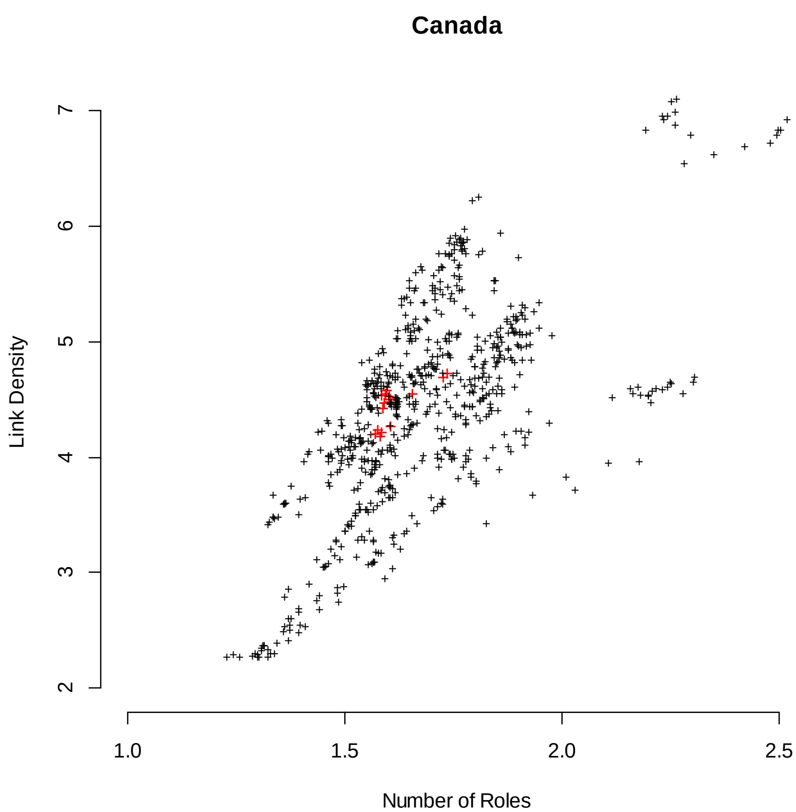
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Link Density
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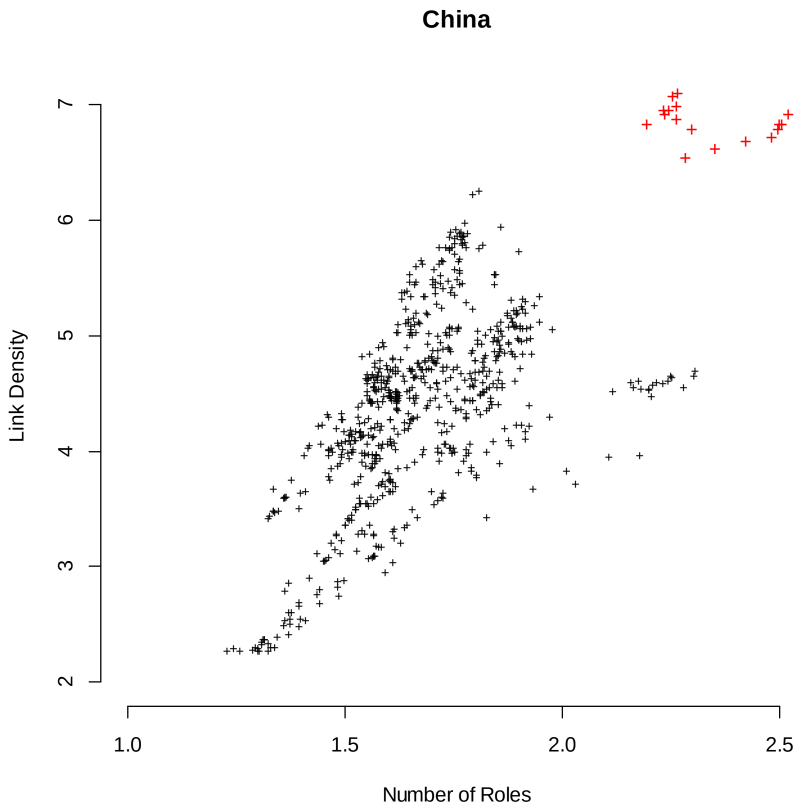
China
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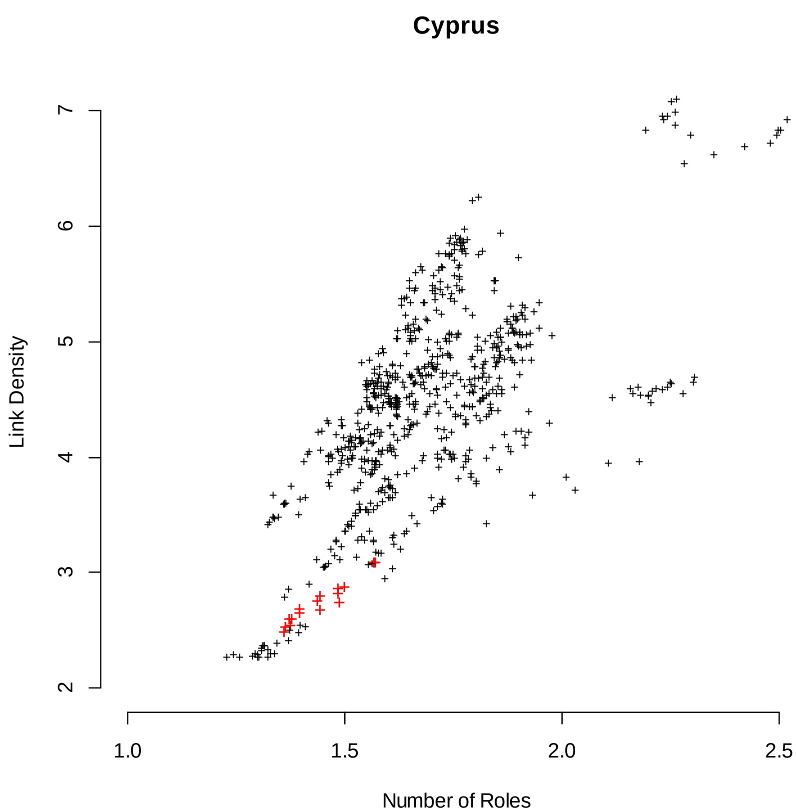
Cyprus
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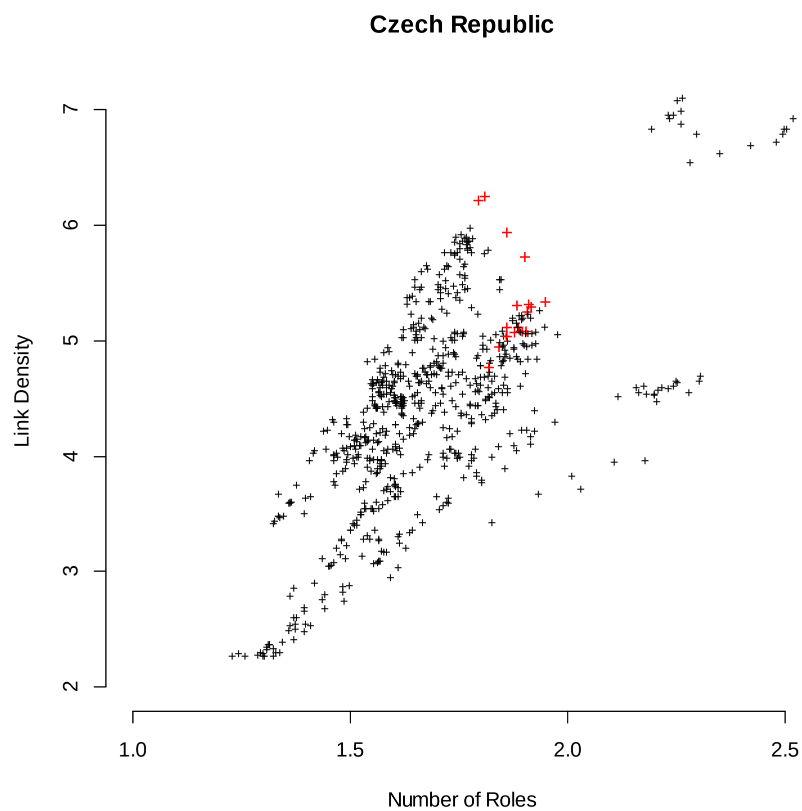
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Link Density
Number of Roles
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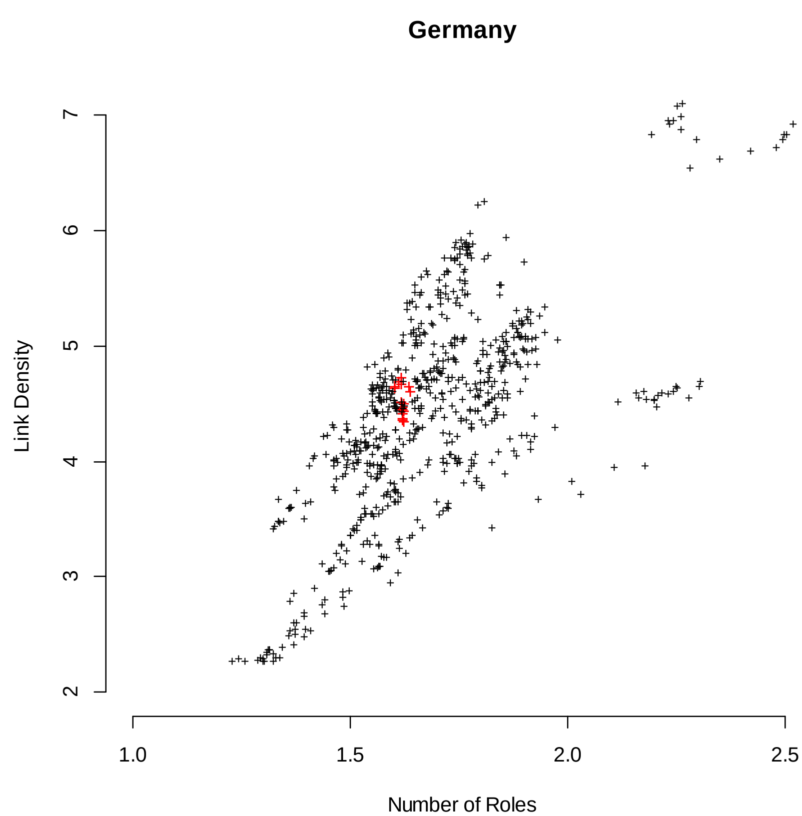
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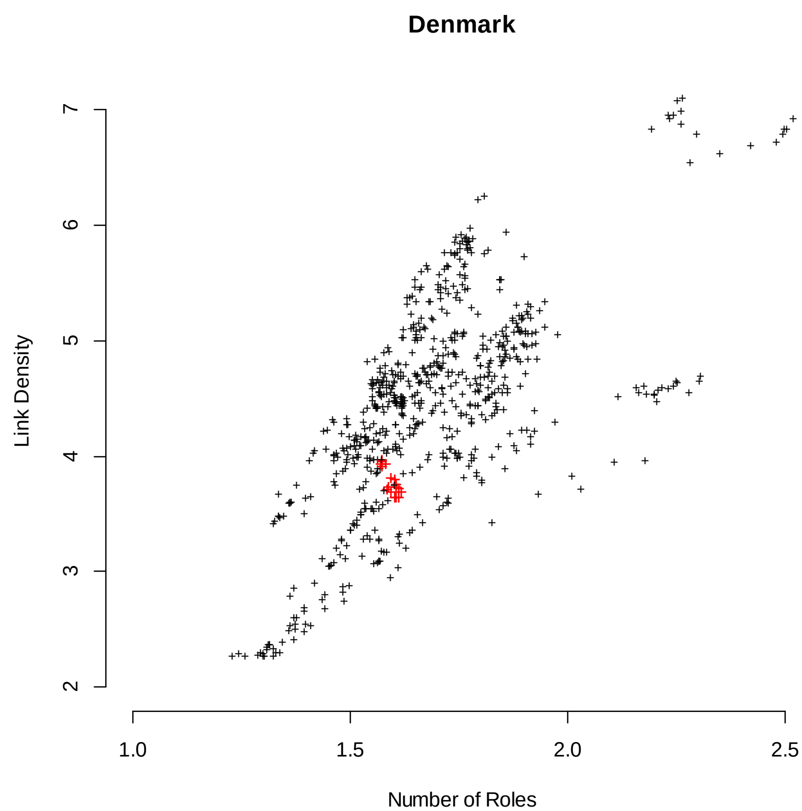
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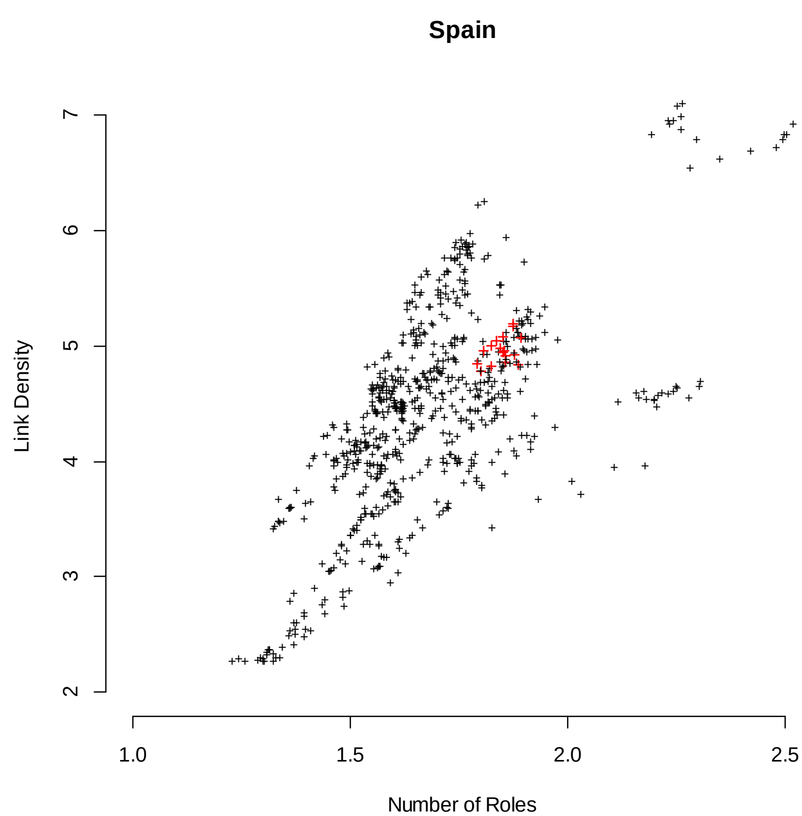
1.5
2.0
2.5
Number of Roles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Link Density
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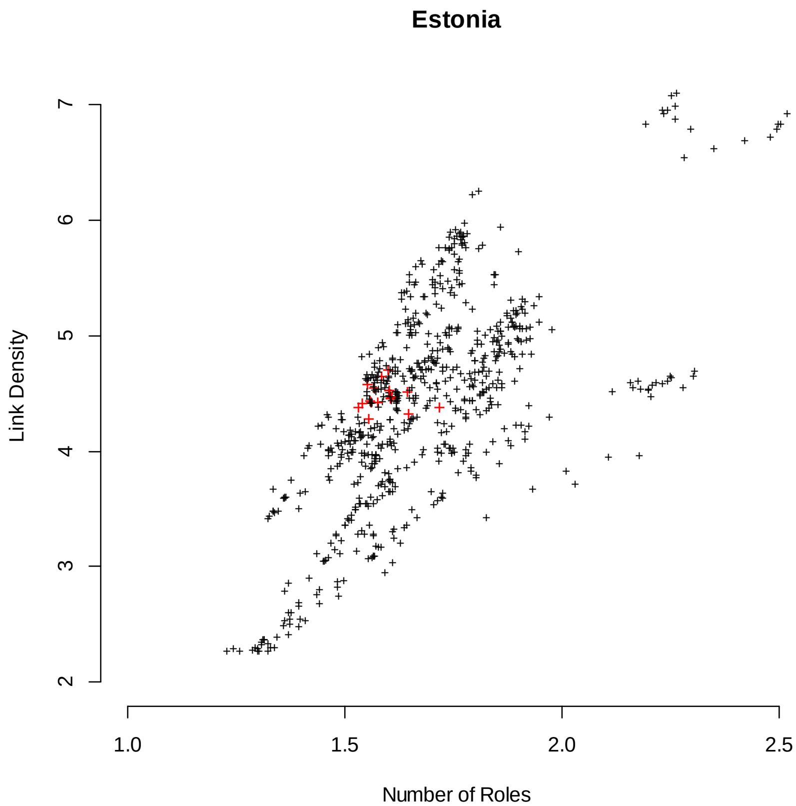
2.5
Number of Roles


Estonia
Link Density
Number of Roles
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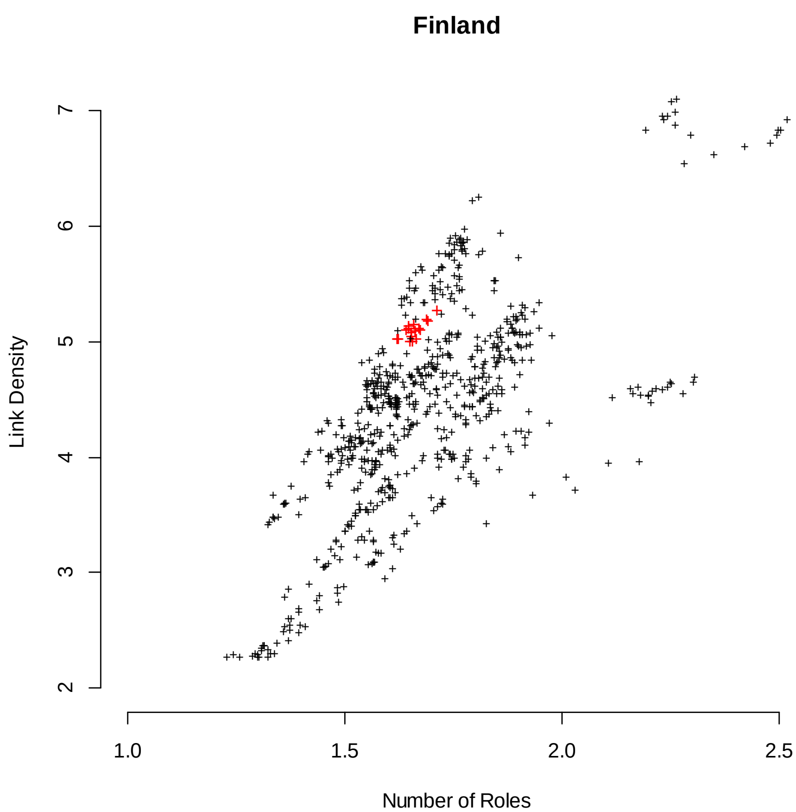
Finland
Link Density
Number of Roles
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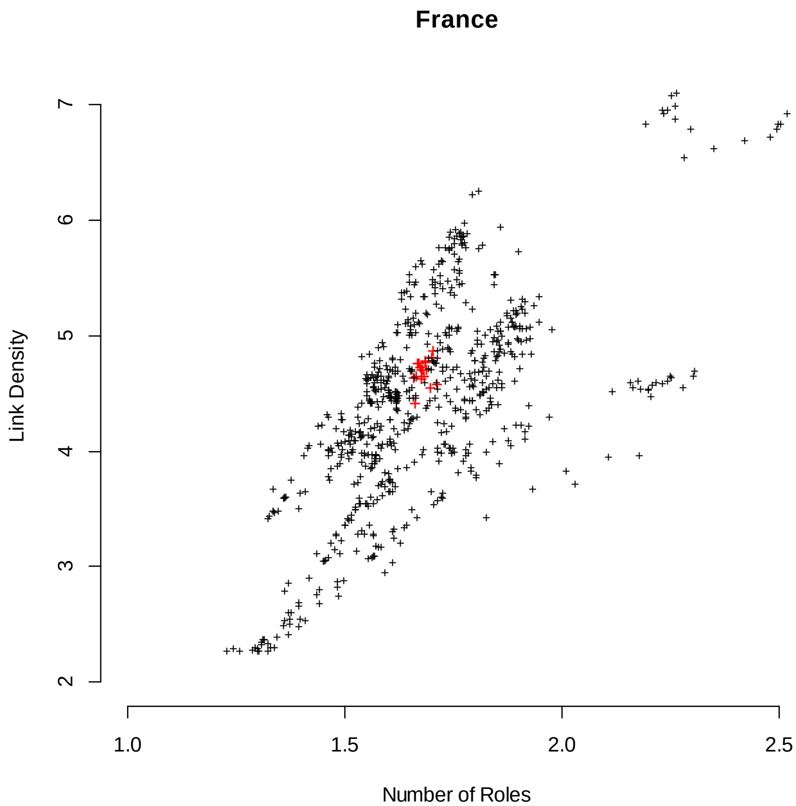
France
Link Density
Number of Roles
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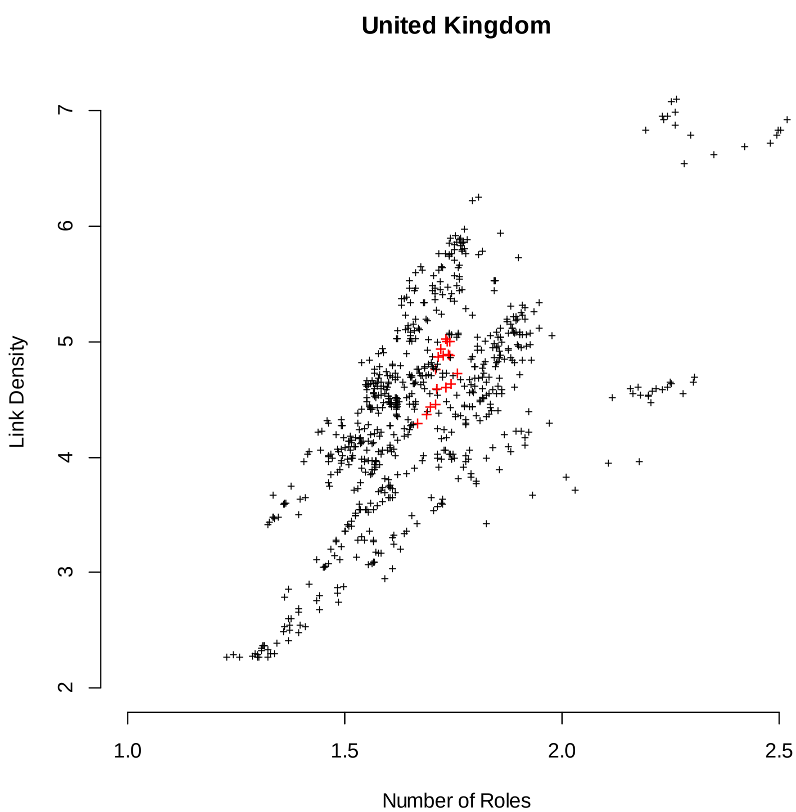
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Link Density
Number of Roles
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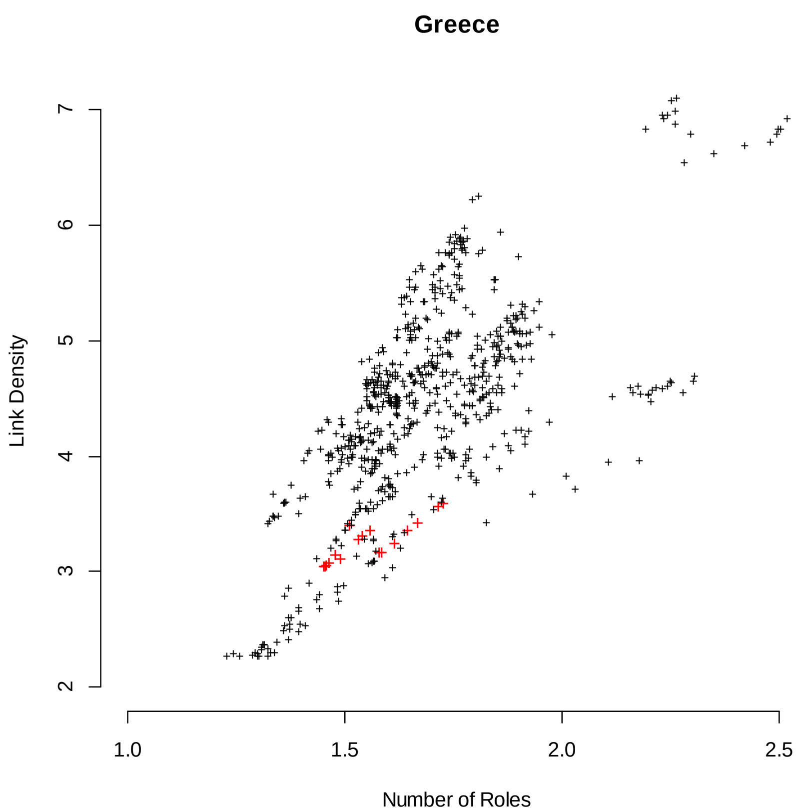
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Link Density
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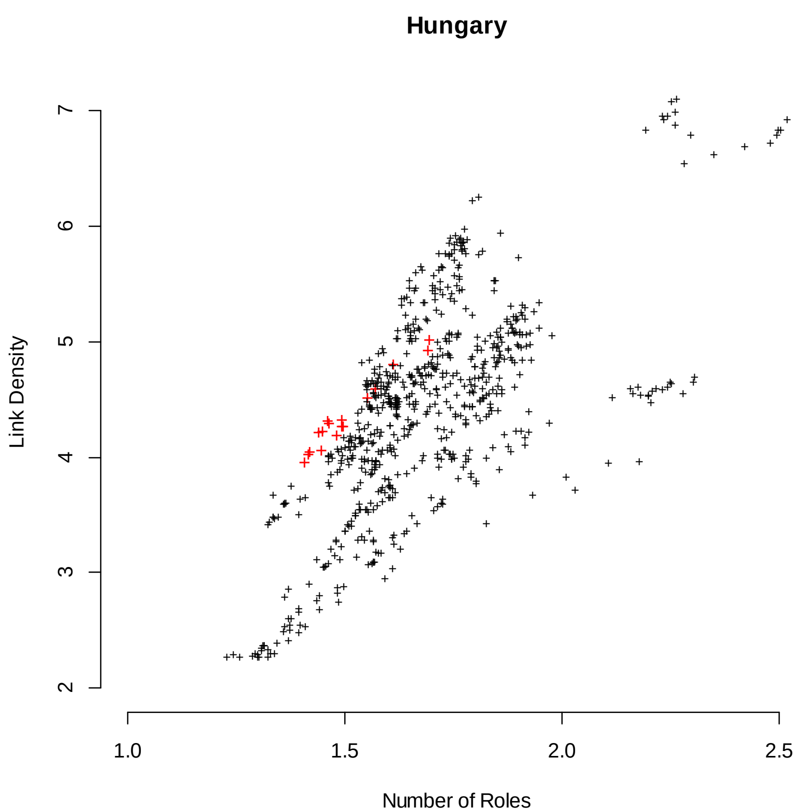
2.5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Link Density
Number of Roles
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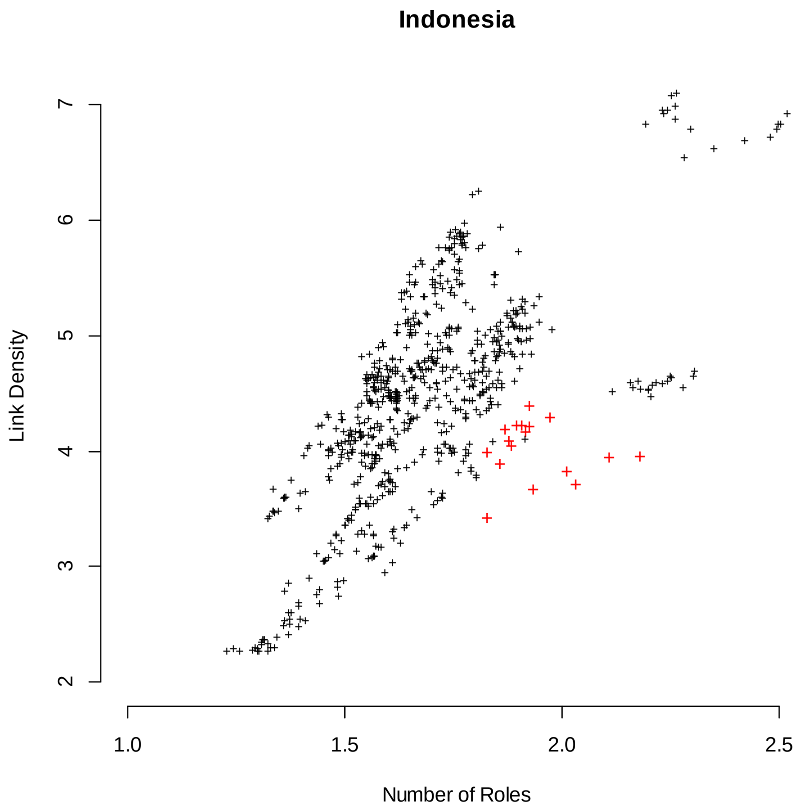
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Link Density
Number of Roles
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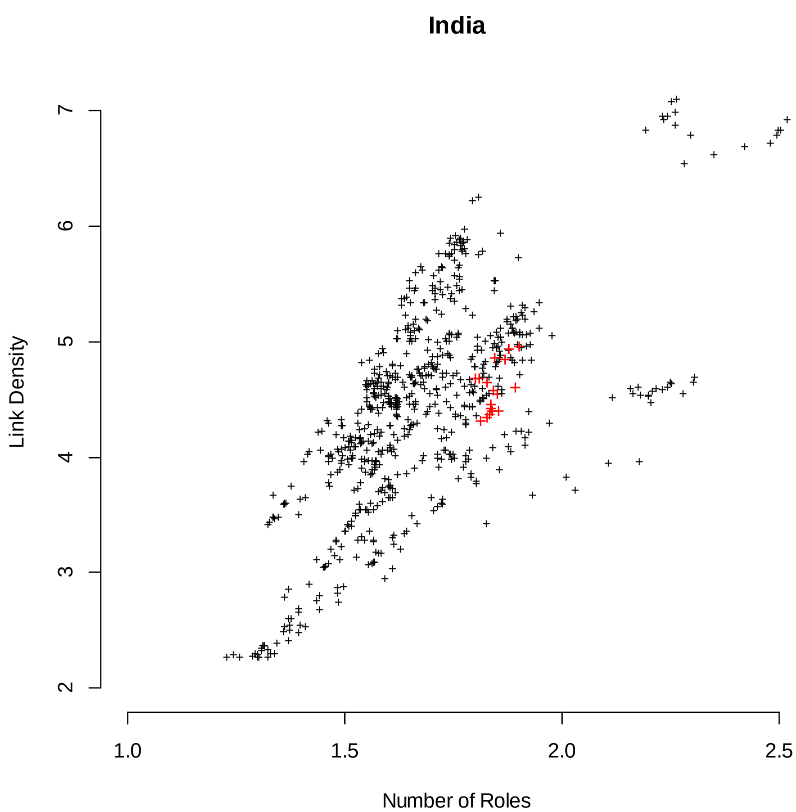
India
Link Density
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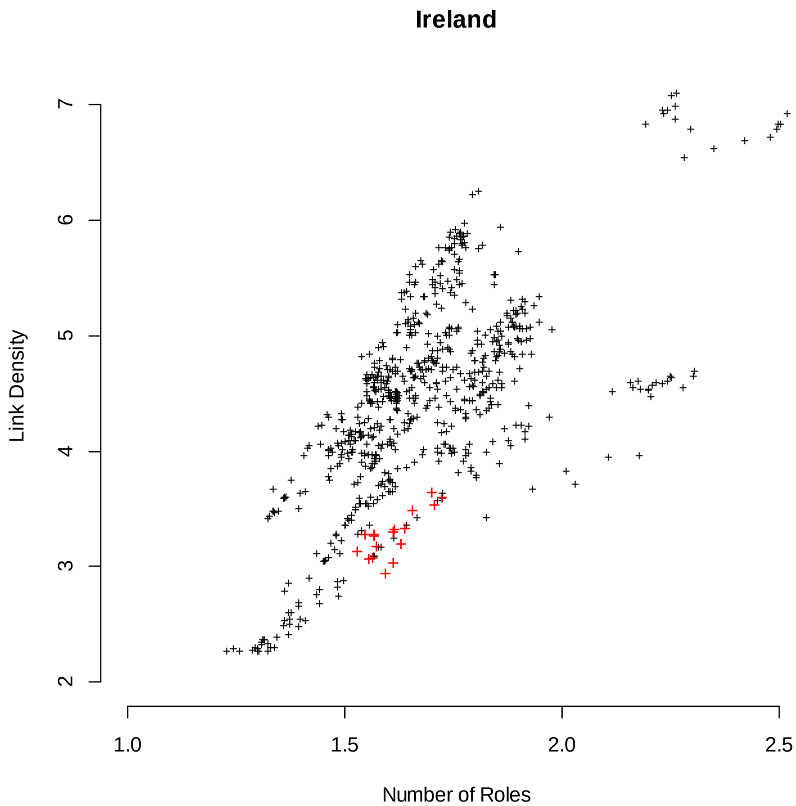
Ireland
Link Density
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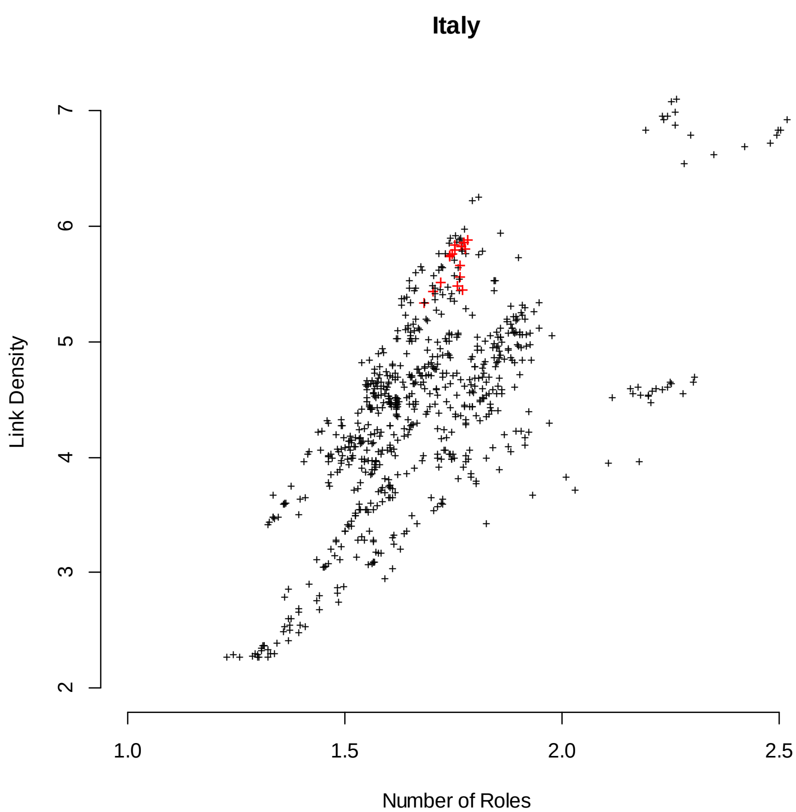
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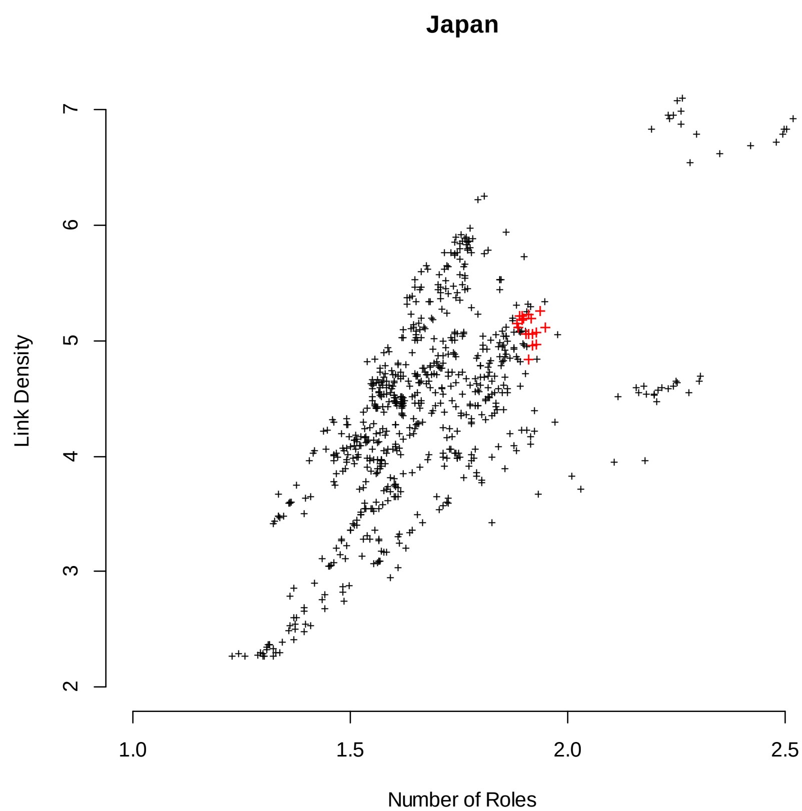
Japan
Link Density
Number of Roles
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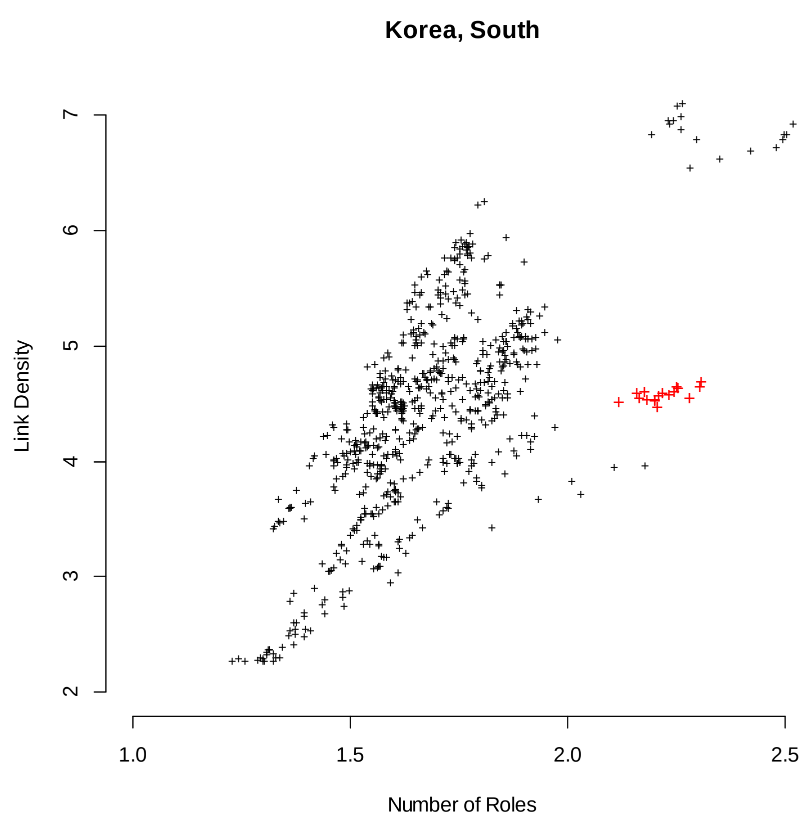
Korea, South
Link Density
Number of Roles
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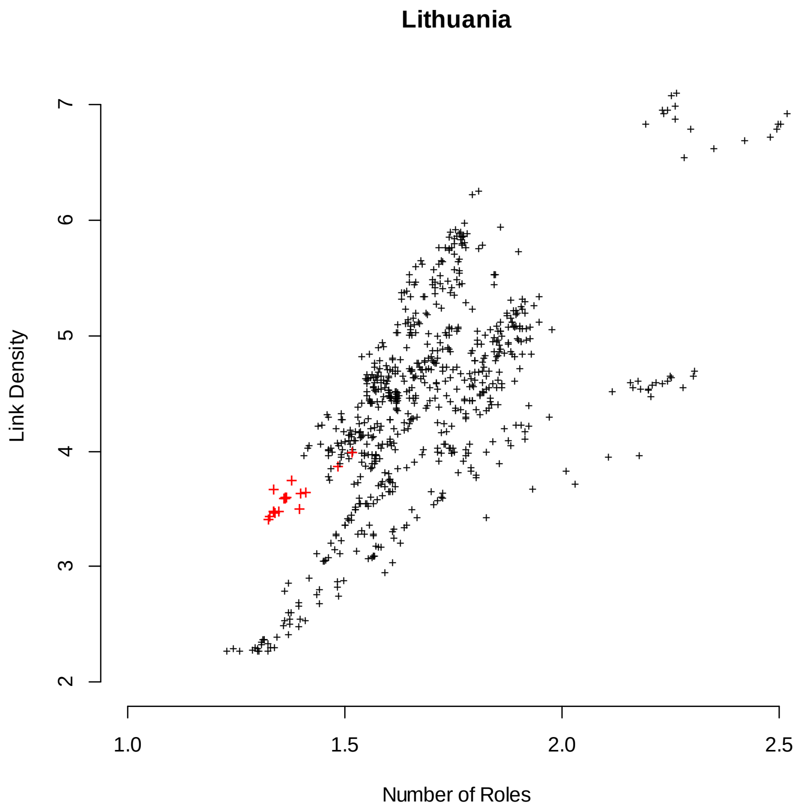
Lithuania
Link Density
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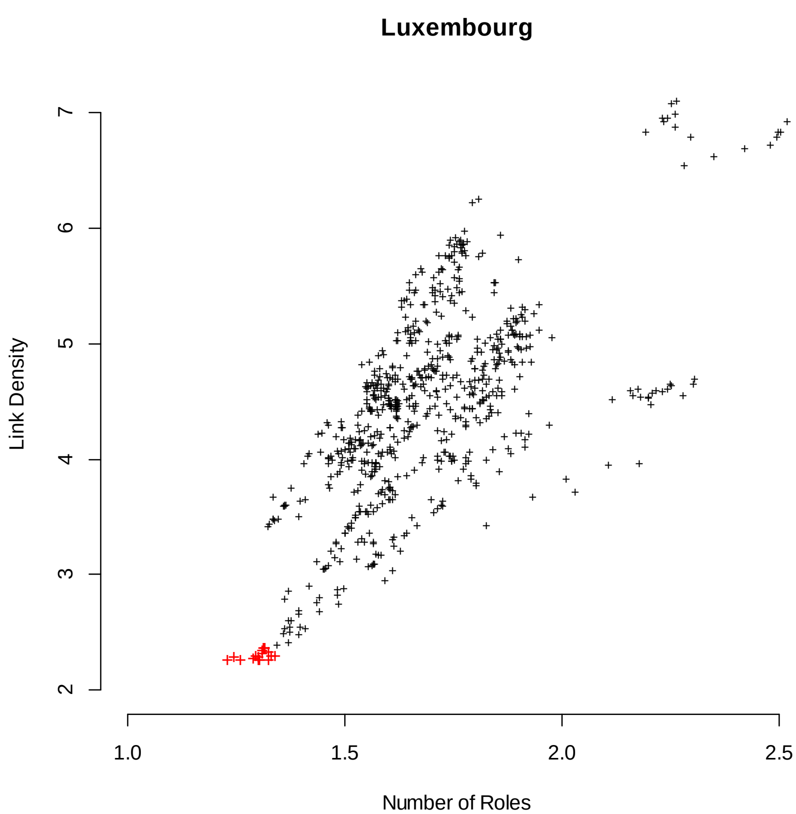
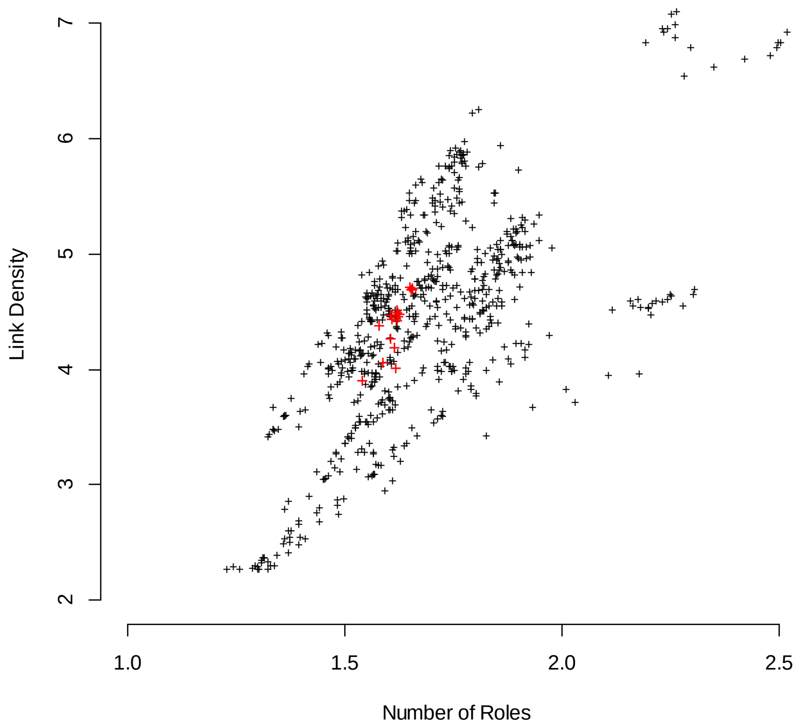
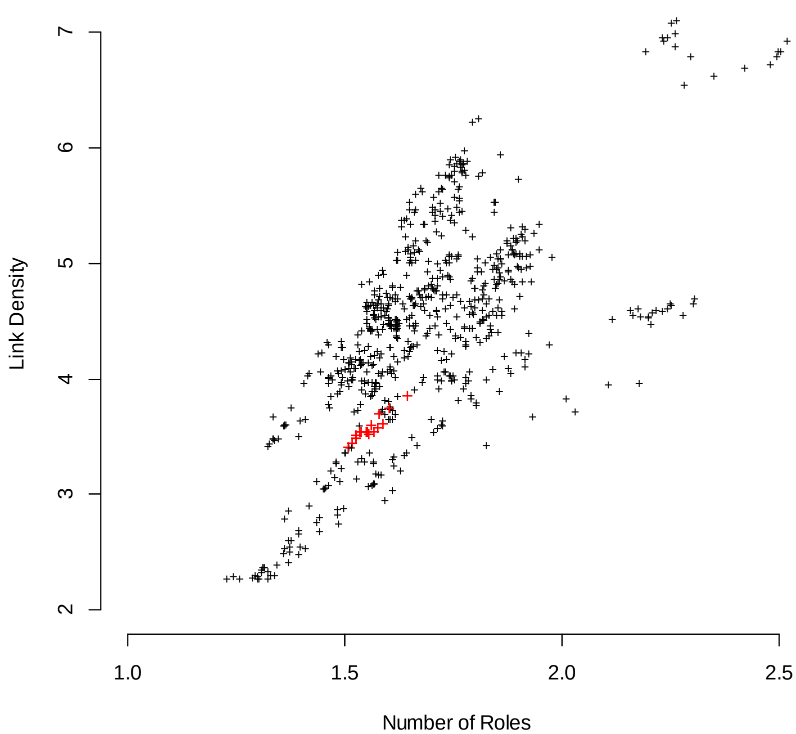
6
7
1.0
1.5
2.0
2.5
Number of Roles

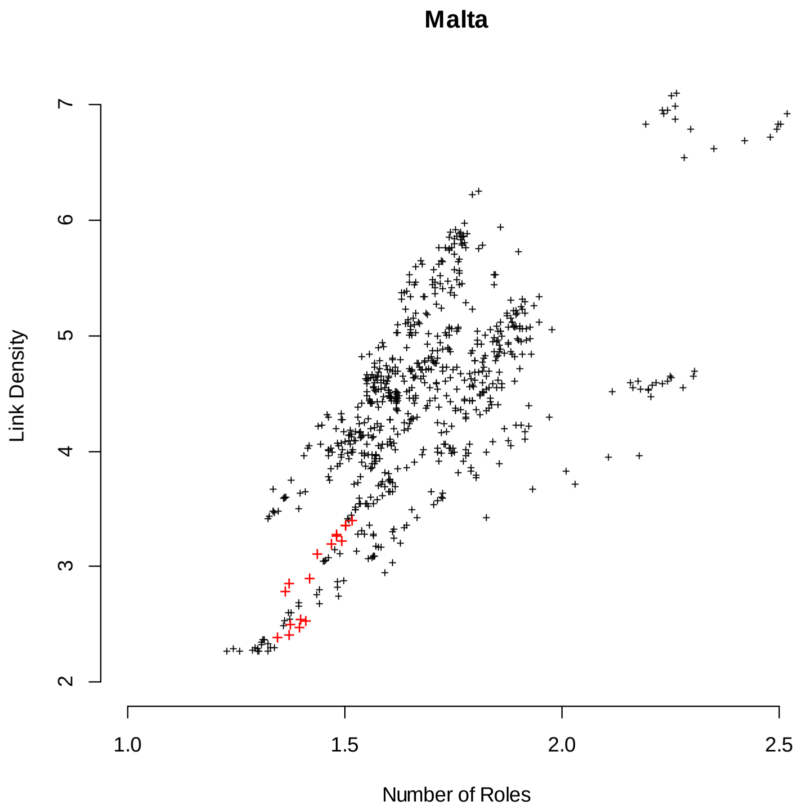

Luxembourg
Link Density
2
3
4
5
6
7
1.0
1.5
2.0
2.5
Number of Roles

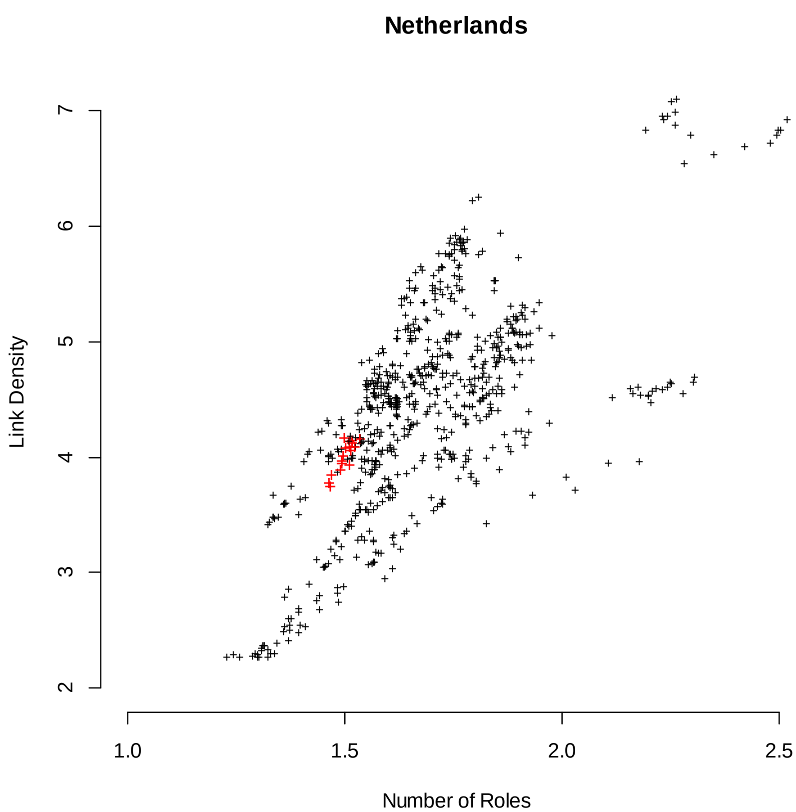
Latvia

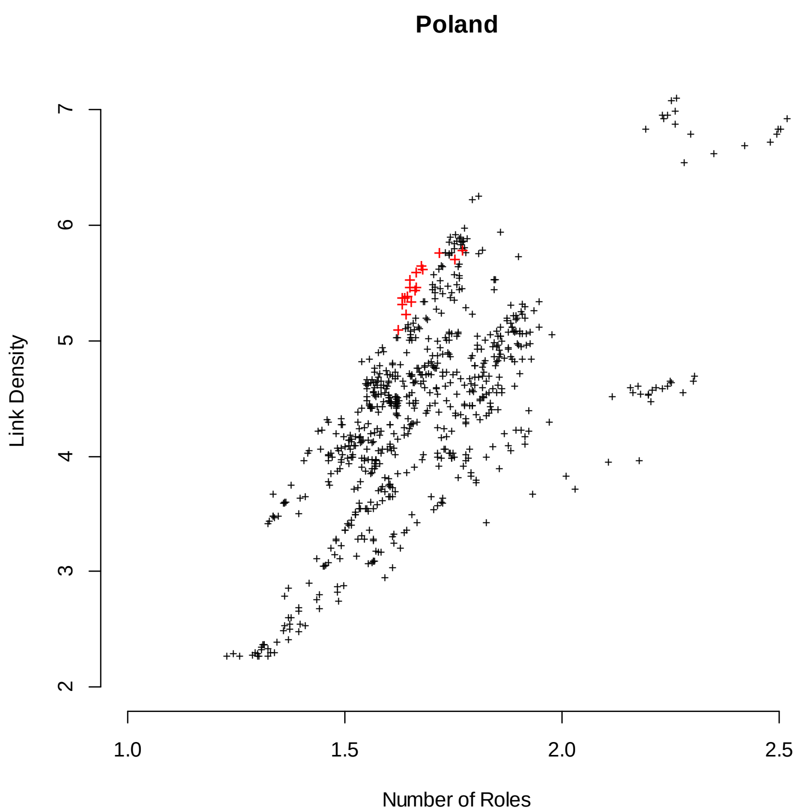


Mexico

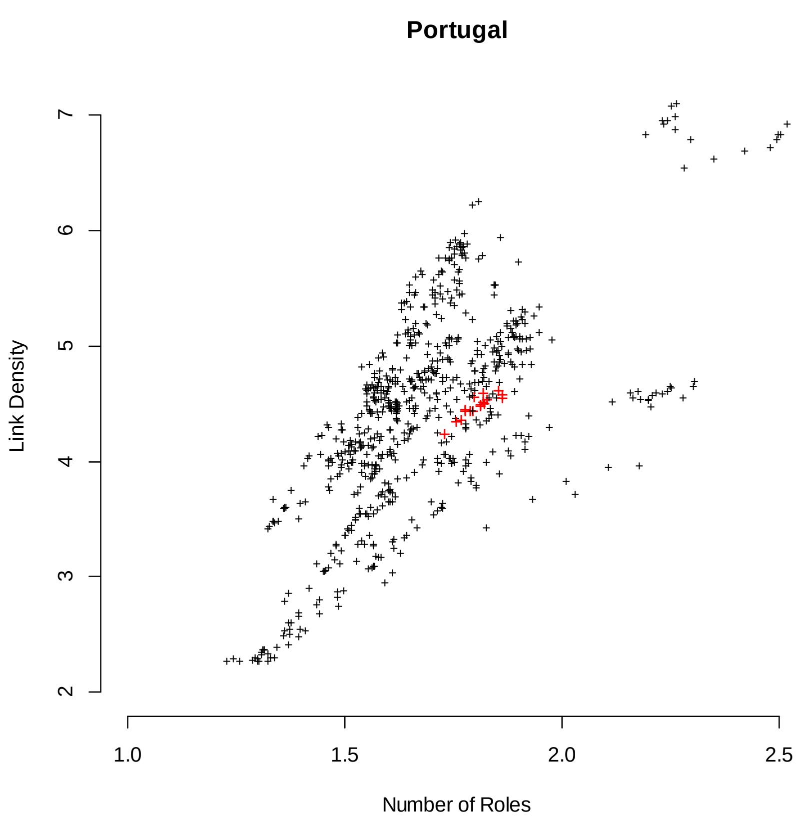



Malta
Link Density
Number of Roles
1.0
1.5
2.0
2.5
2
3
4
5
6
7


Netherlands
Link Density
Number of Roles
1.0
1.5
2.0
2.5
2
3
4
5
6
7

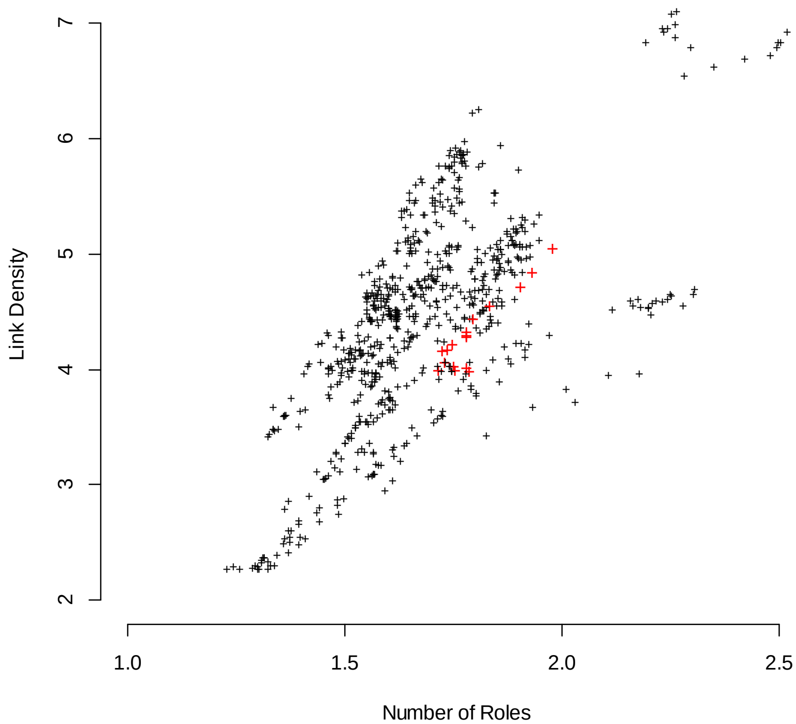


Poland
Link Density
Number of Roles
1.0
1.5
2.0
2.5
2
3
4
5
6
7

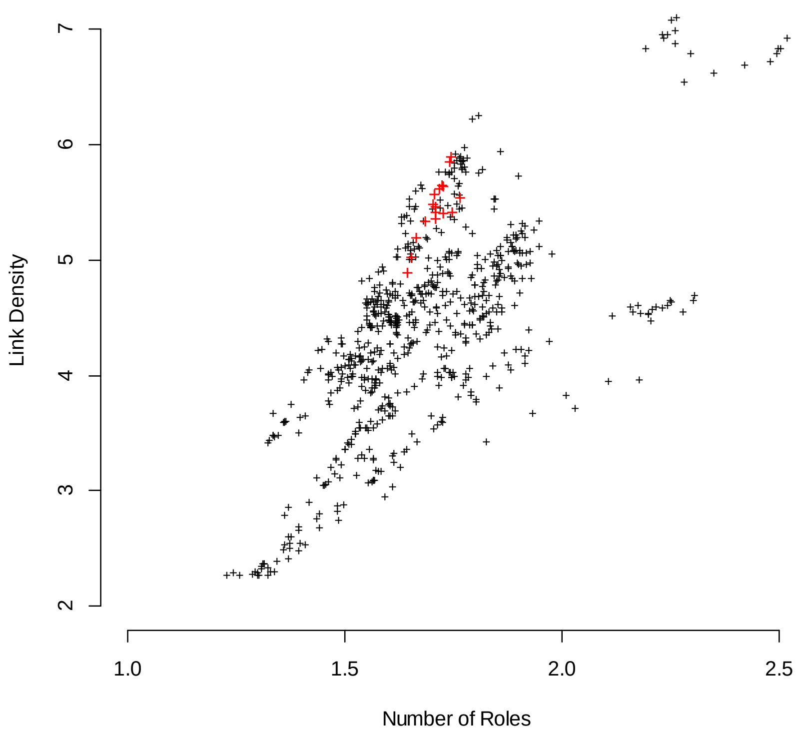


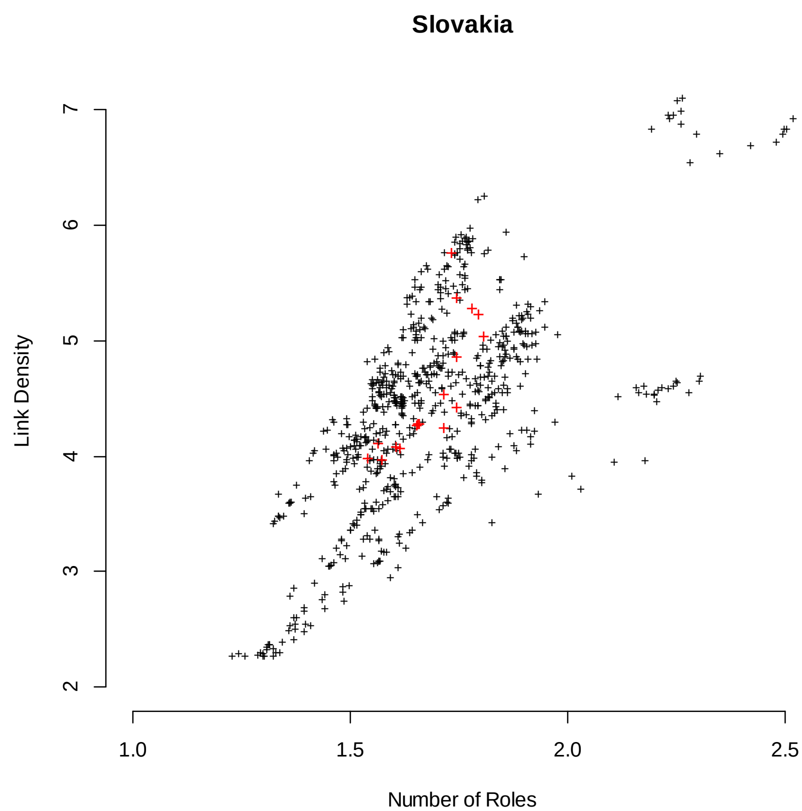
Portugal
Link Density
Number of Roles
1.0
1.5
2.0
2.5
2
3
4
5
6
7

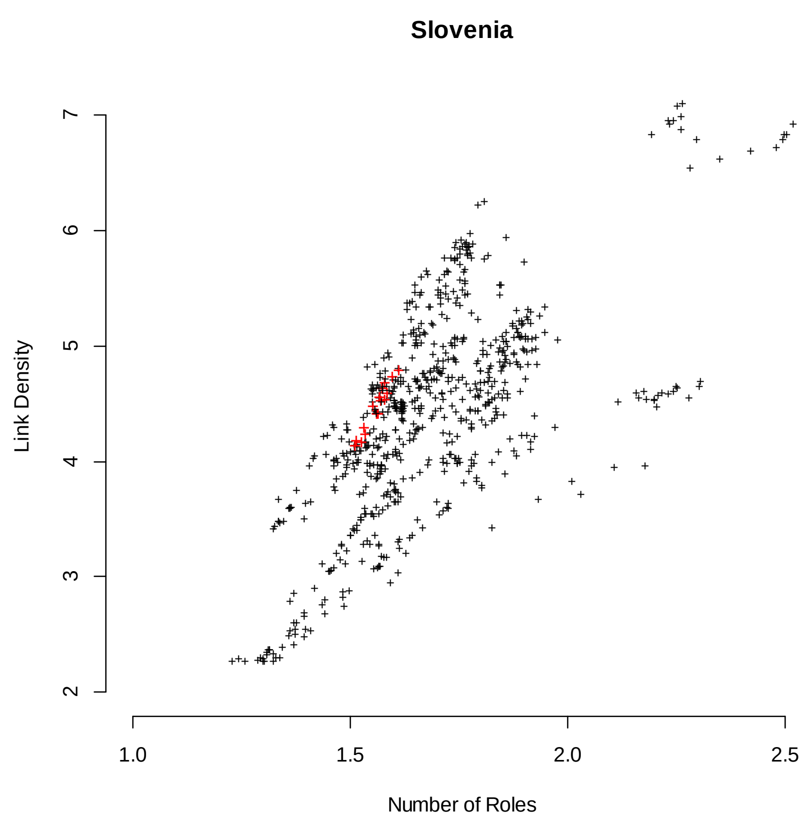
Romania

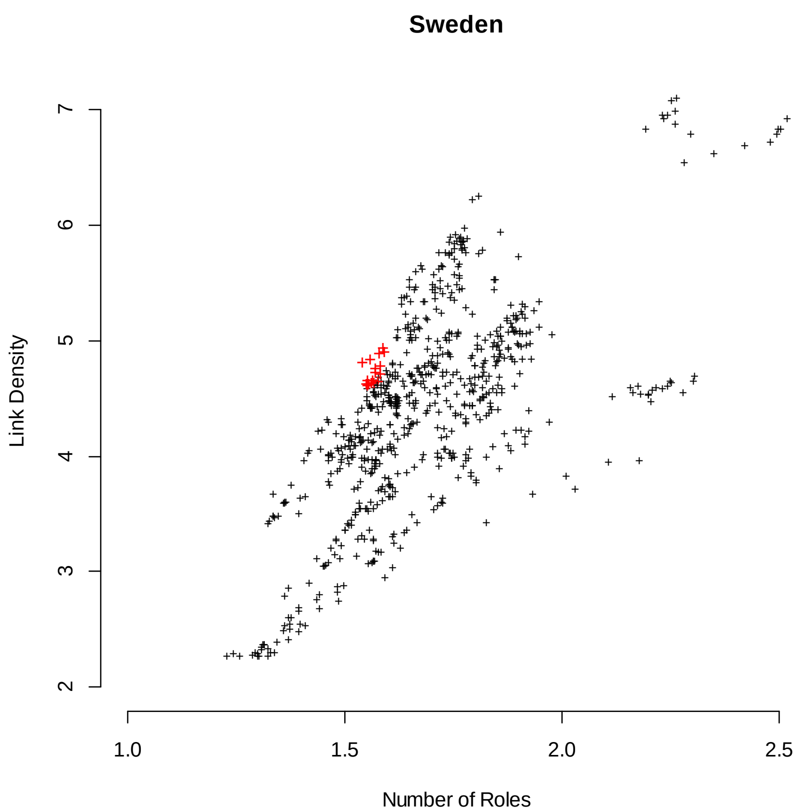


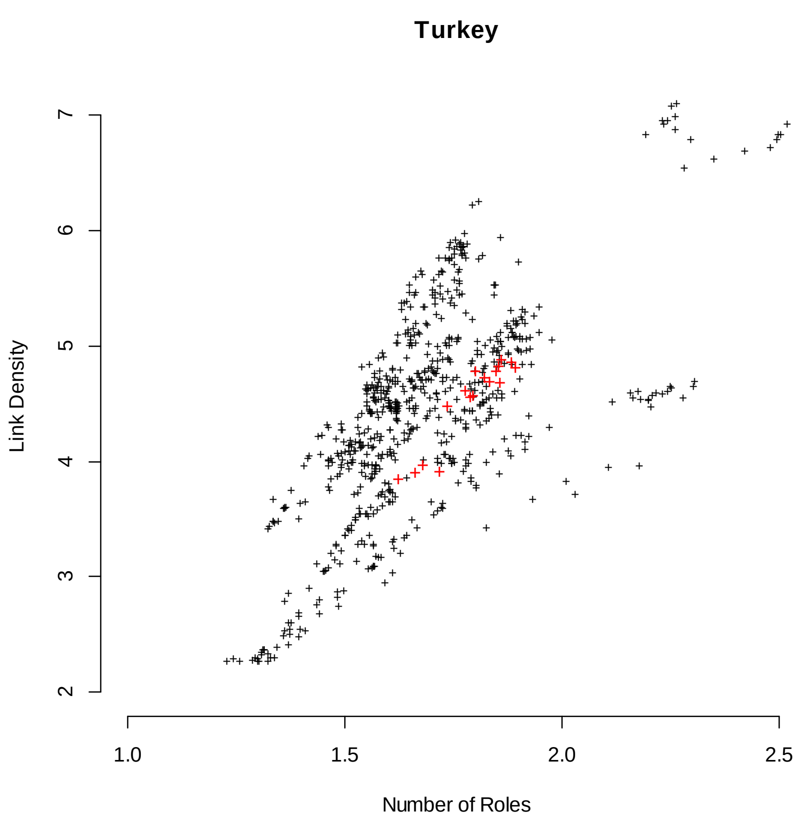
Russia

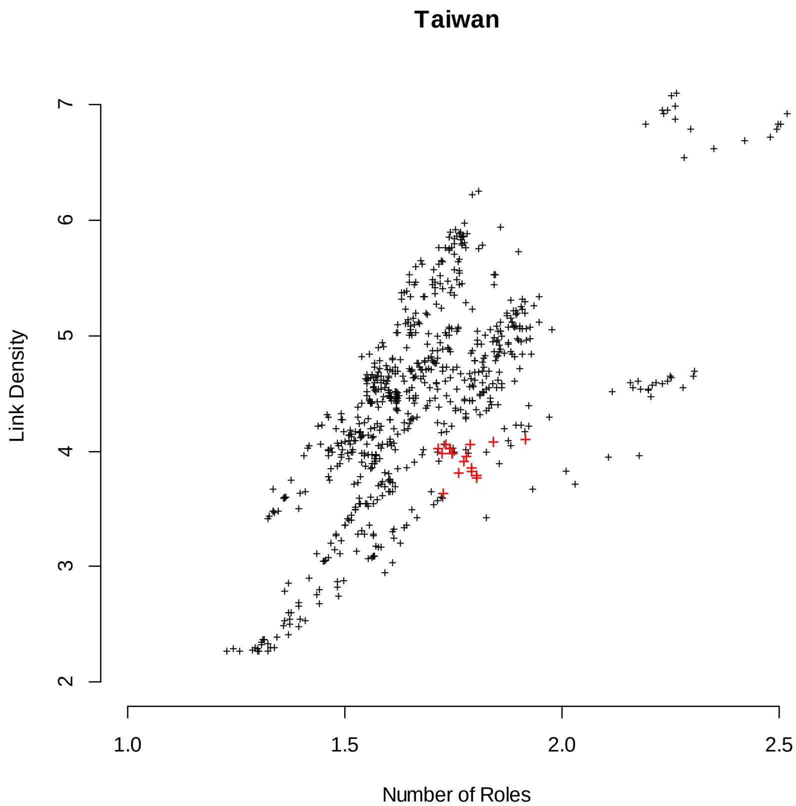


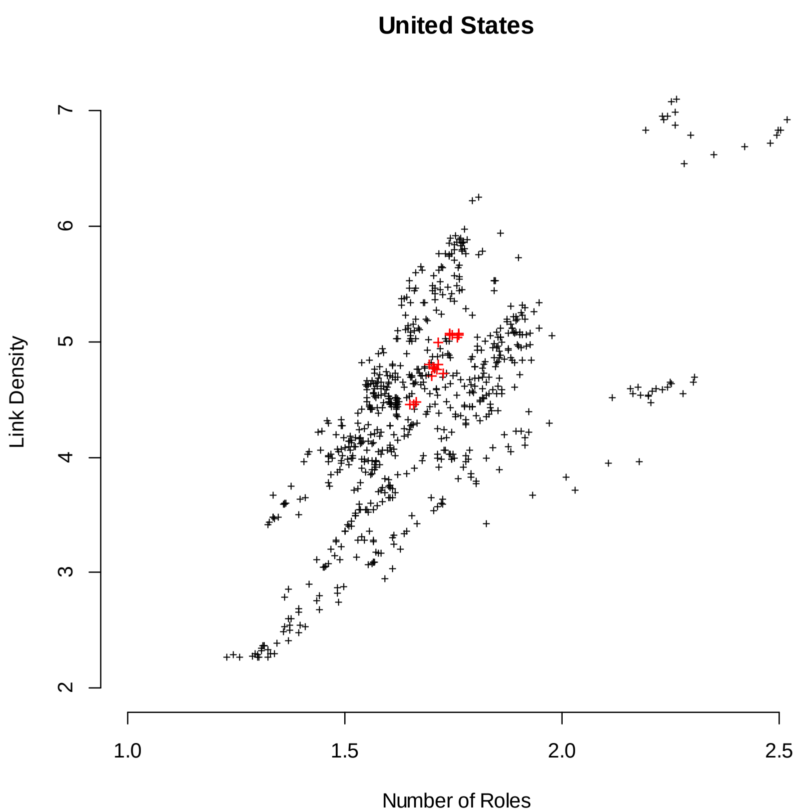

Slovakia
Link Density
Number of Roles
2
3
4
5
6
7
1.0
1.5
2.0
2.5


Slovenia
Link Density
Number of Roles
2
3
4
5
6
7
1.0
1.5
2.0
2.5

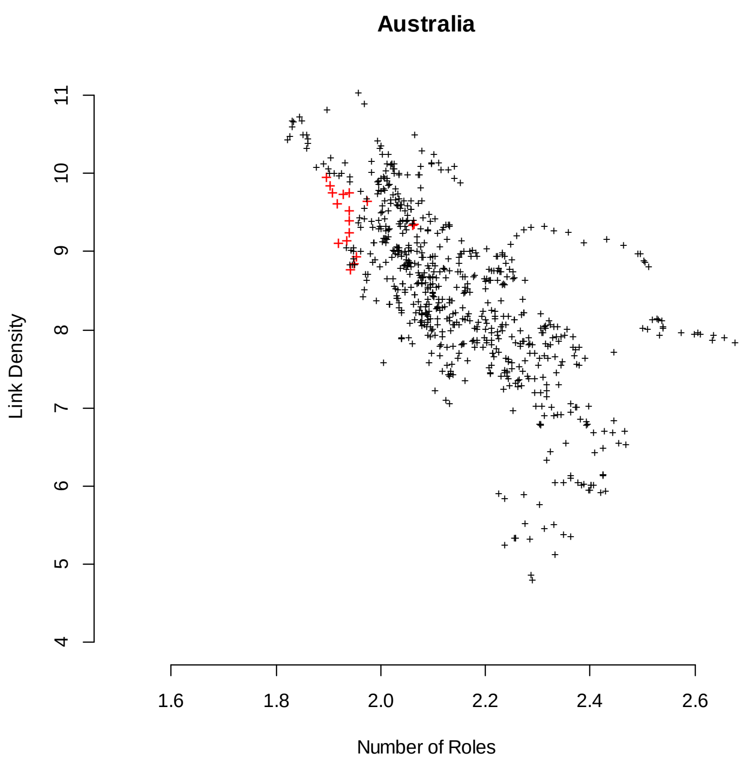

Sweden
Link Density
Number of Roles
2
3
4
5
6
7
1.0
1.5
2.0
2.5

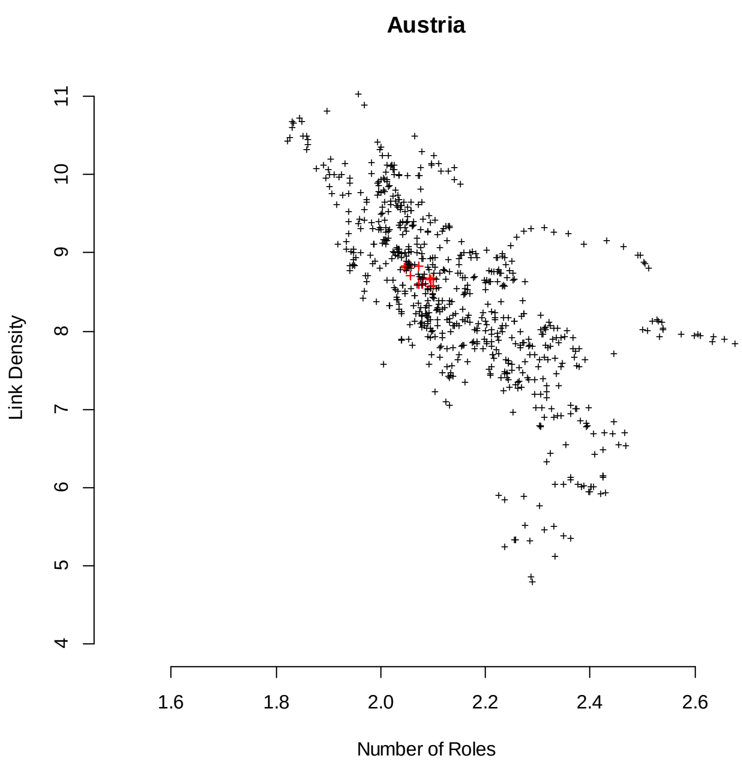

Turkey
Link Density
Number of Roles
2
3
4
5
6
7
1.0
1.5
2.0
2.5

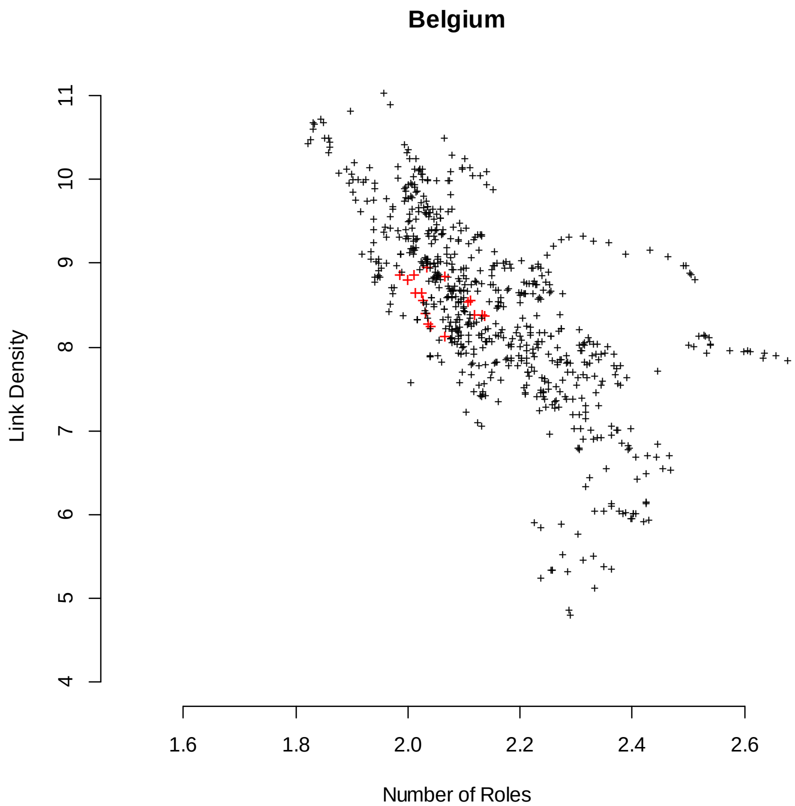

Taiwan
Link Density
Number of Roles
1.0
1.5
2.0
2.5
2
3
4
5
6
7

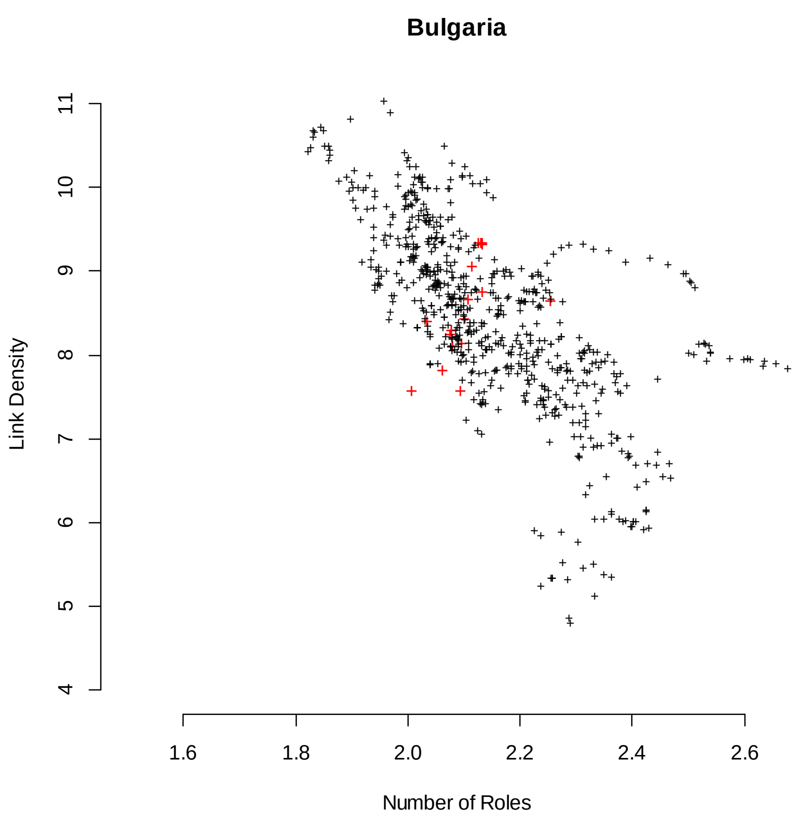

United States
Link Density
Number of Roles
1.0
1.5
2.0
2.5
2
3
4
5
6
7

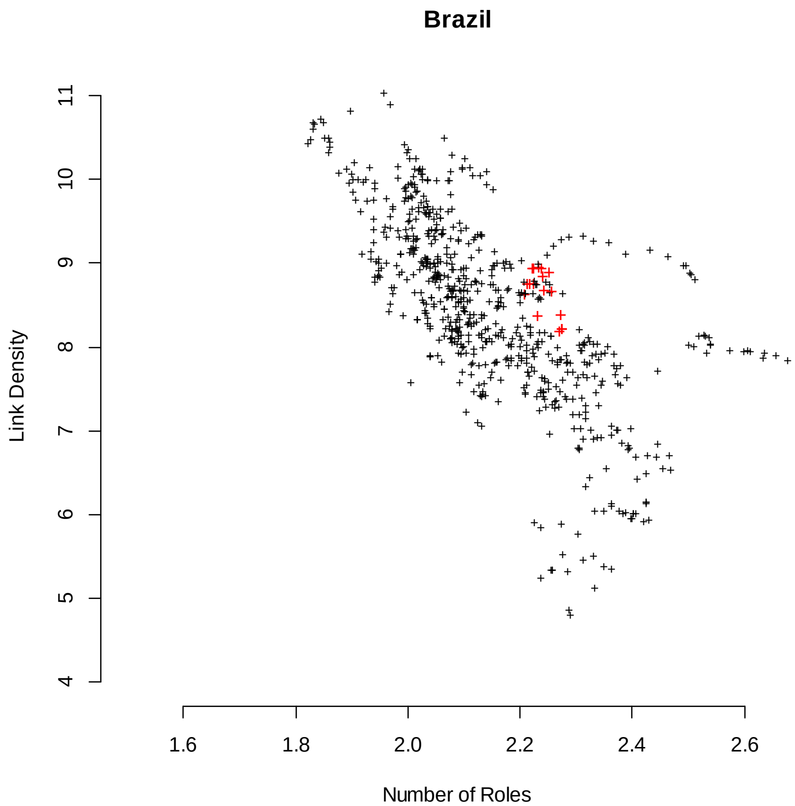
All Years, Individual Countries Highlighted – Closed Model



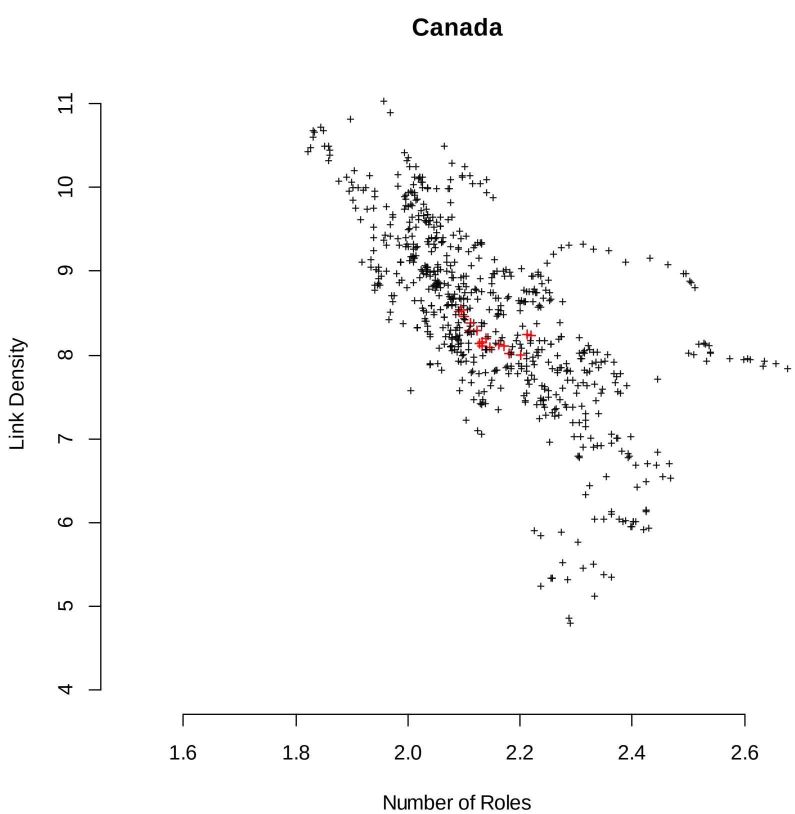



Belgium
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6

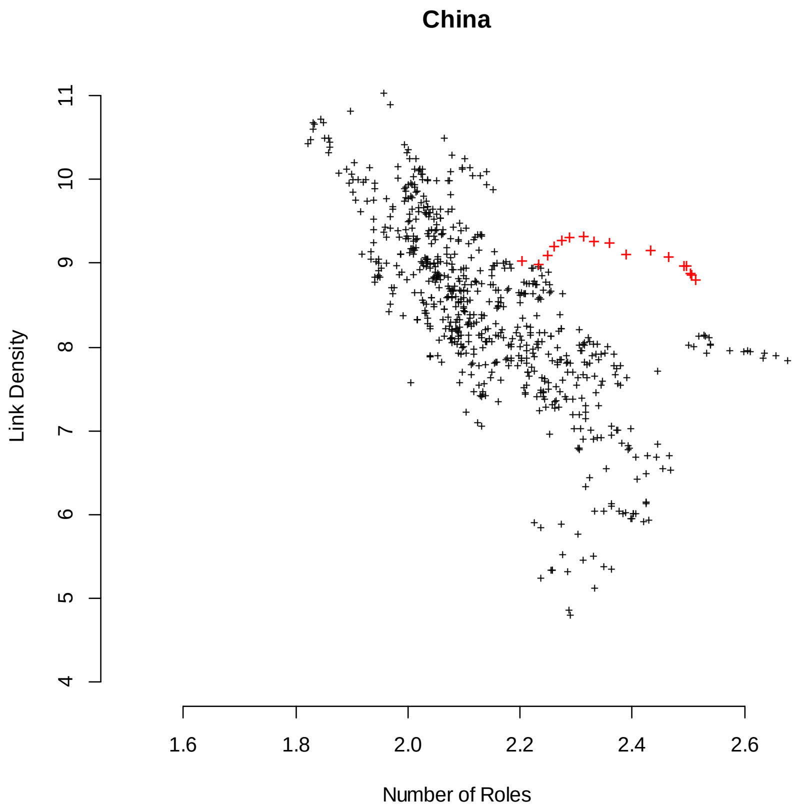

Bulgaria
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6

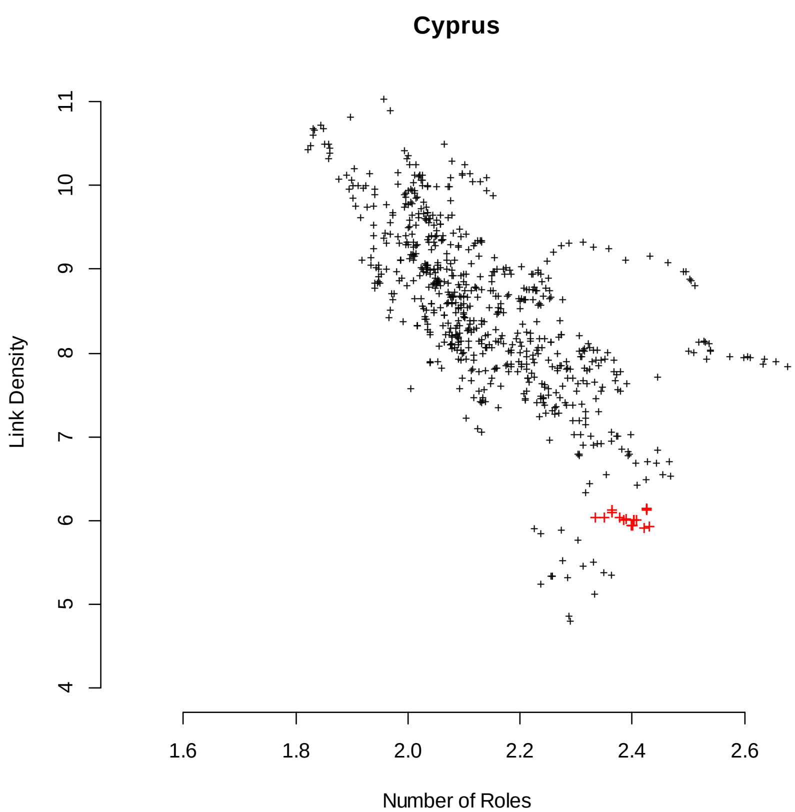


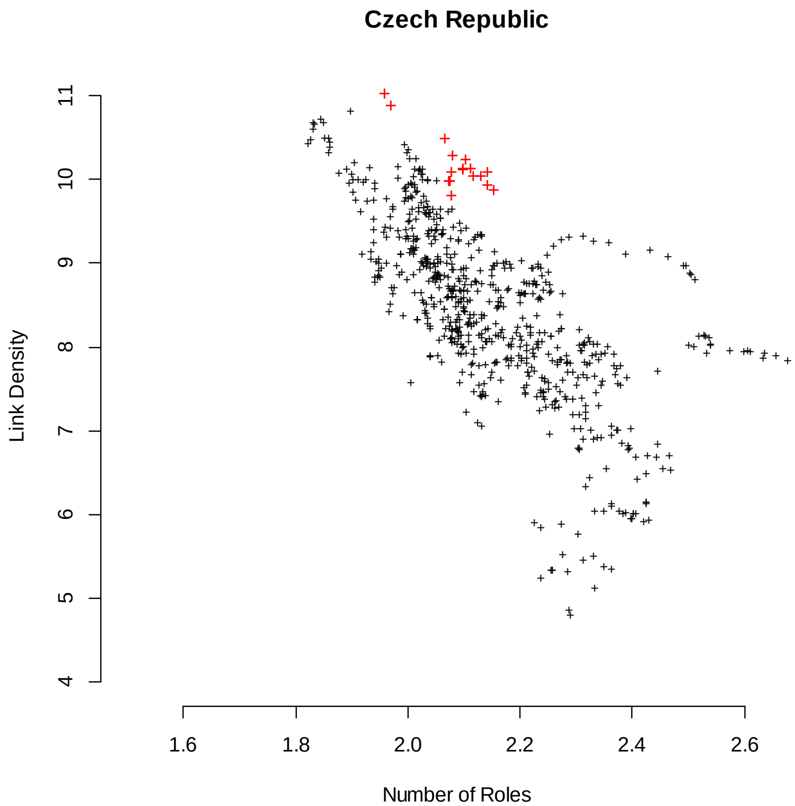
Brazil
Link Density
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6
Number of Roles



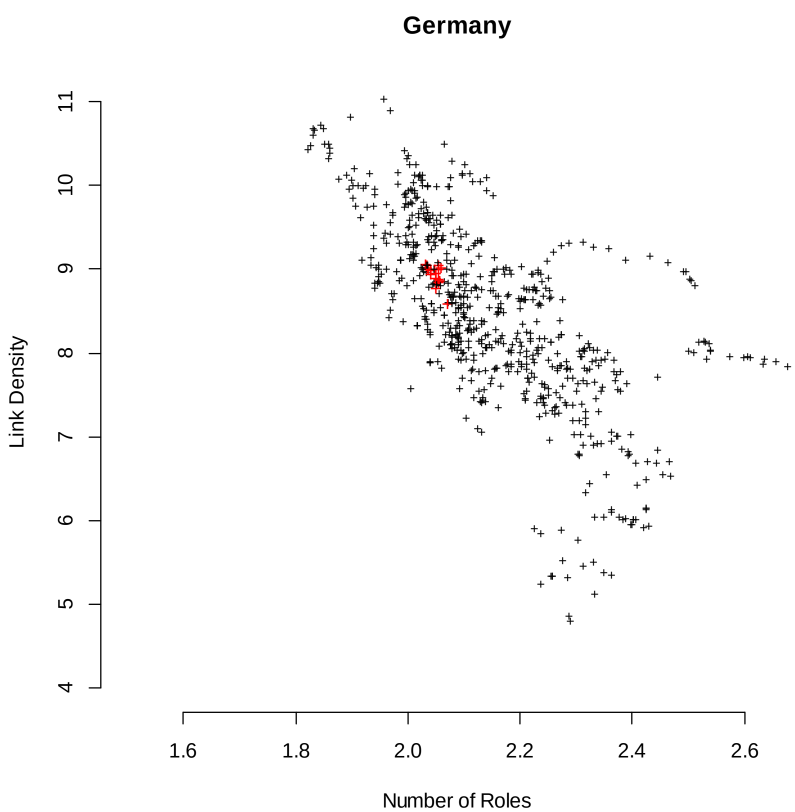
Canada
Link Density
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6
Number of Roles


China
Link Density
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6
Number of Roles

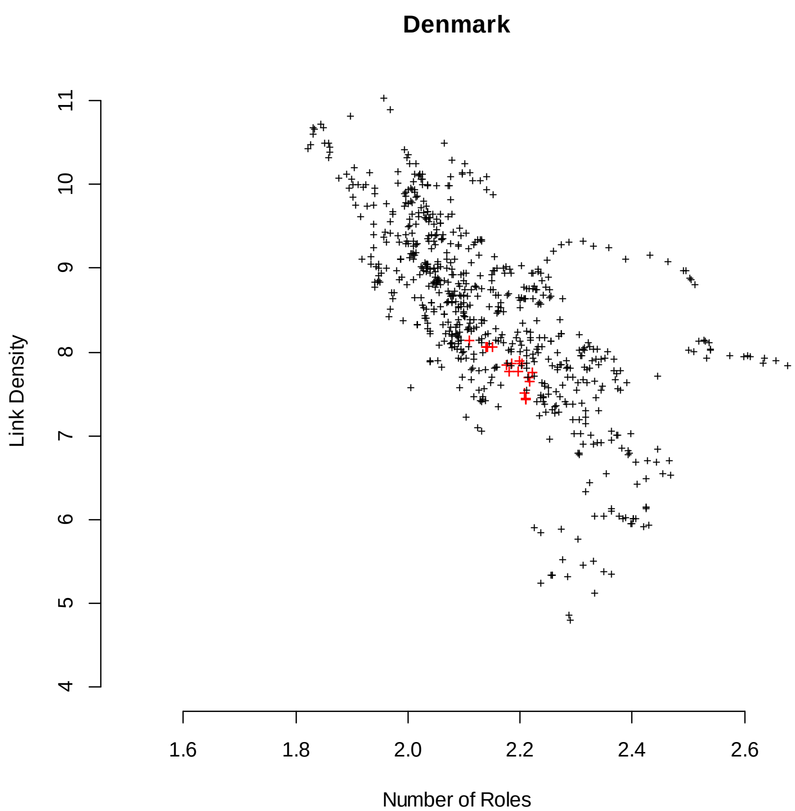

Cyprus
Link Density
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6
Number of Roles

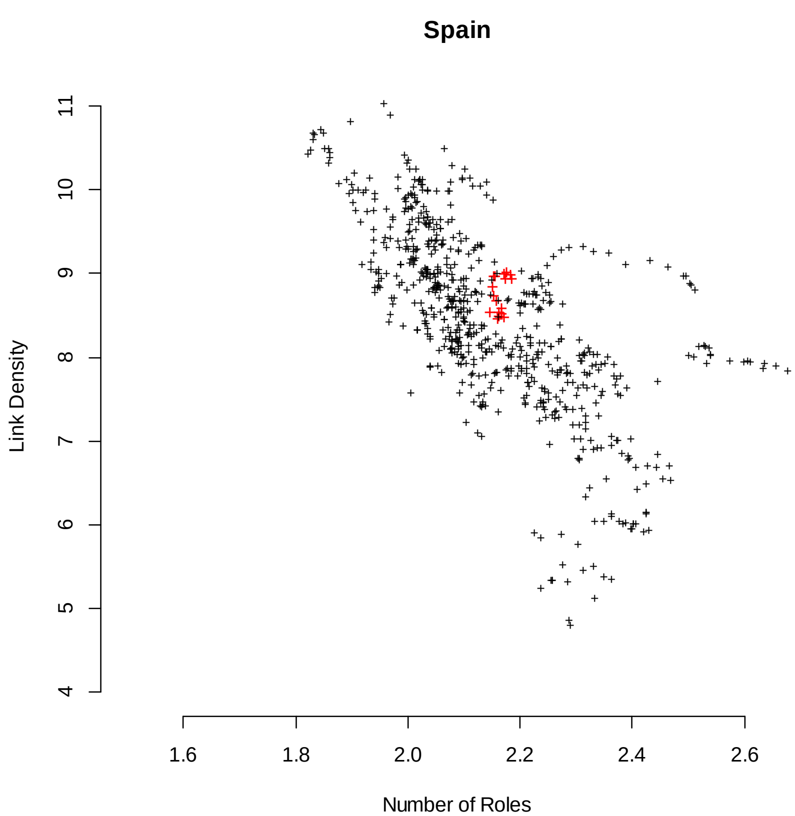


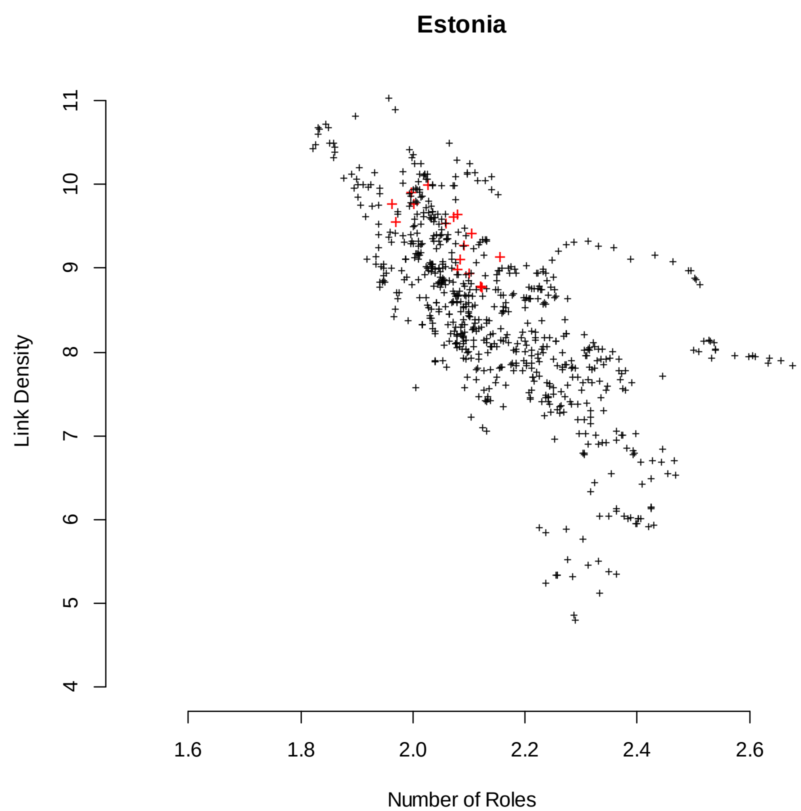
Czech Republic
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6



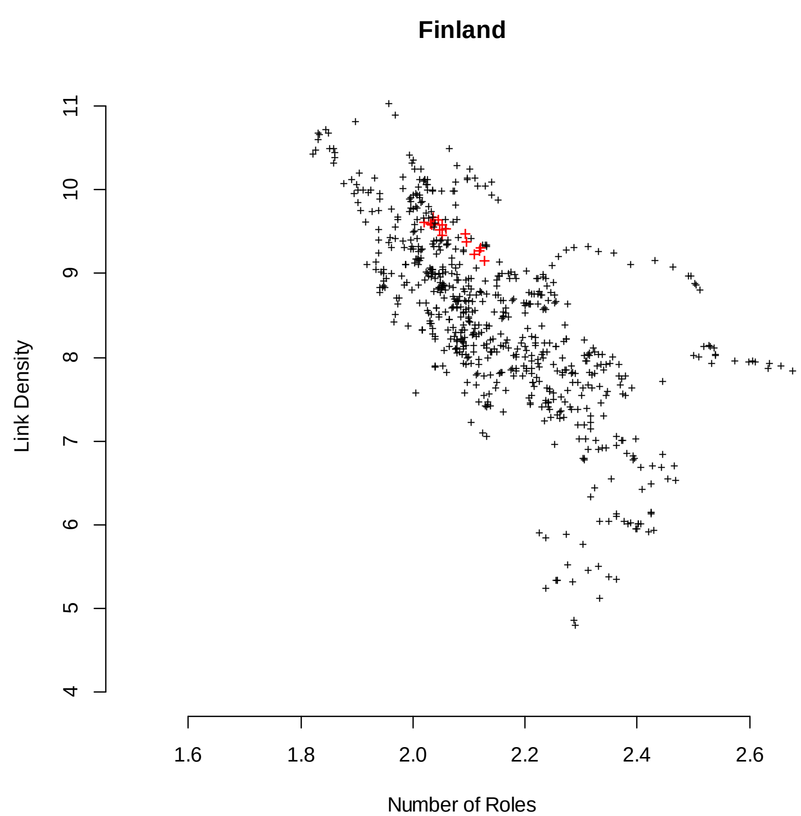
Germany
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6


Denmark
Link Density
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6
Number of Roles

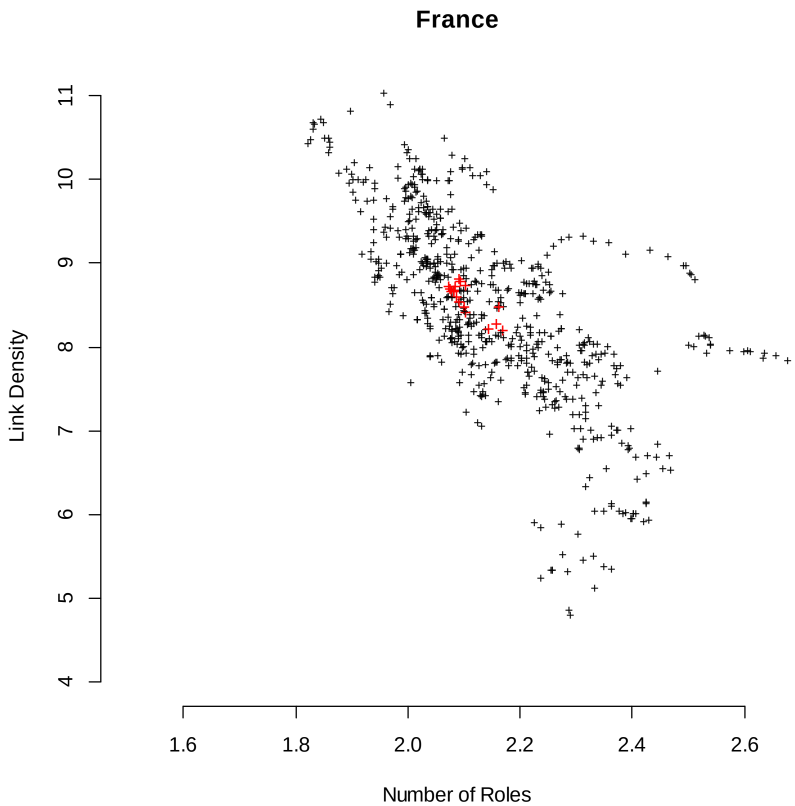

Spain
Link Density
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6
Number of Roles

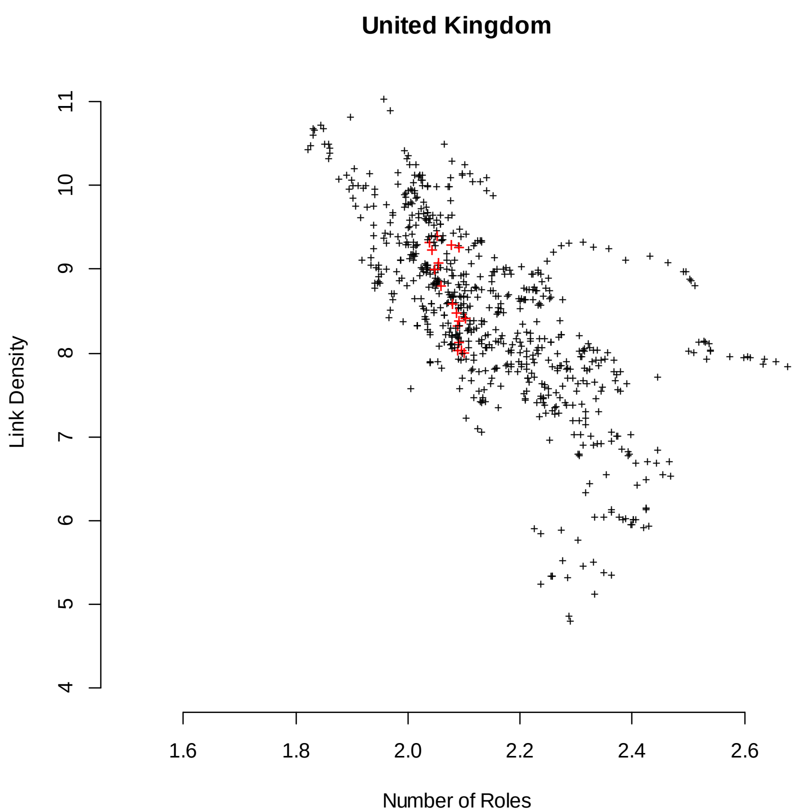


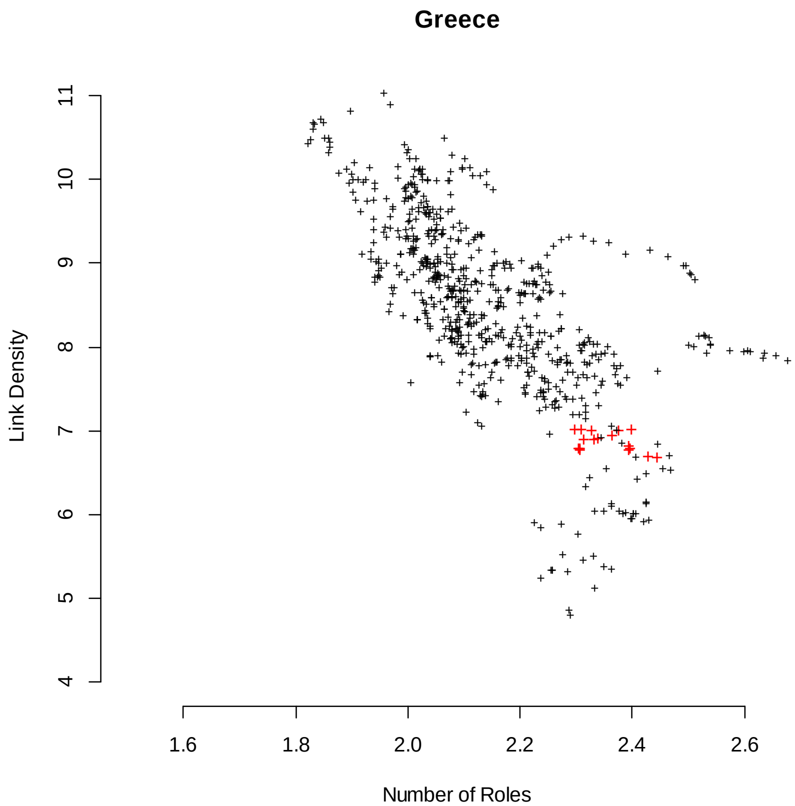
Estonia
Link Density
Number of Roles

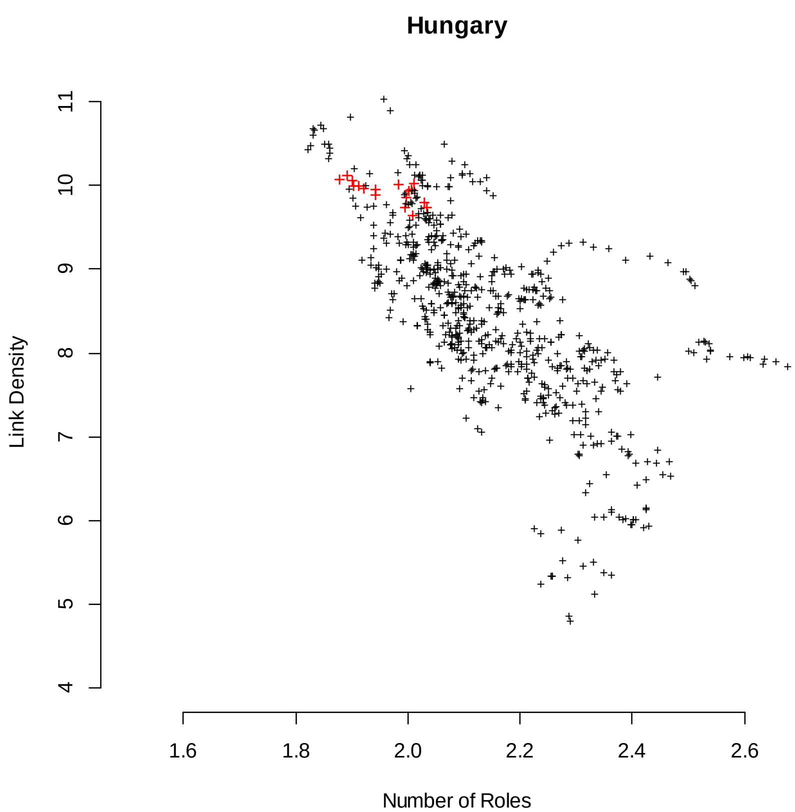


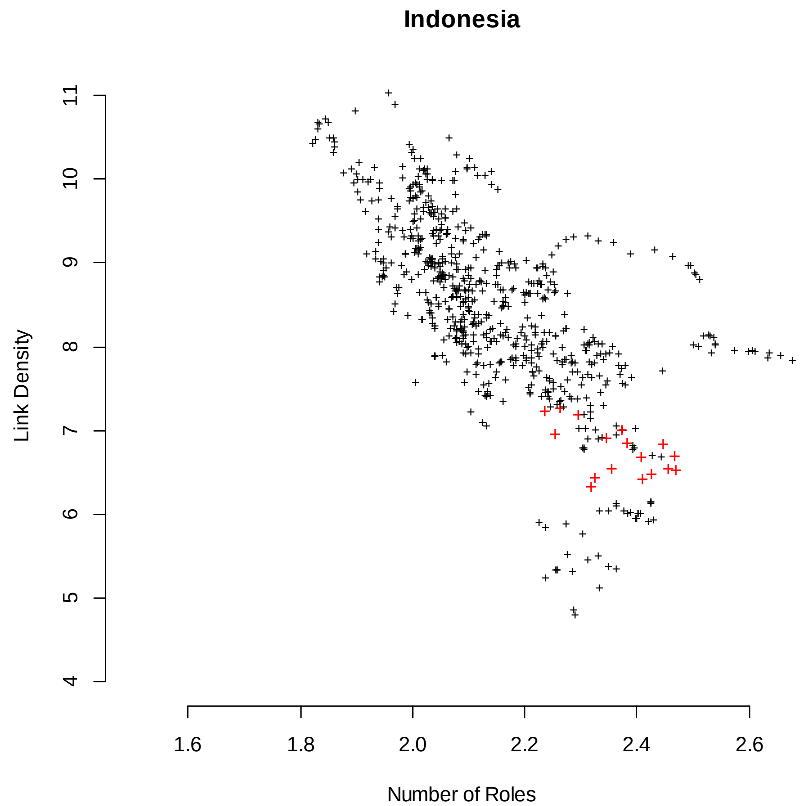
Finland
Link Density
Number of Roles

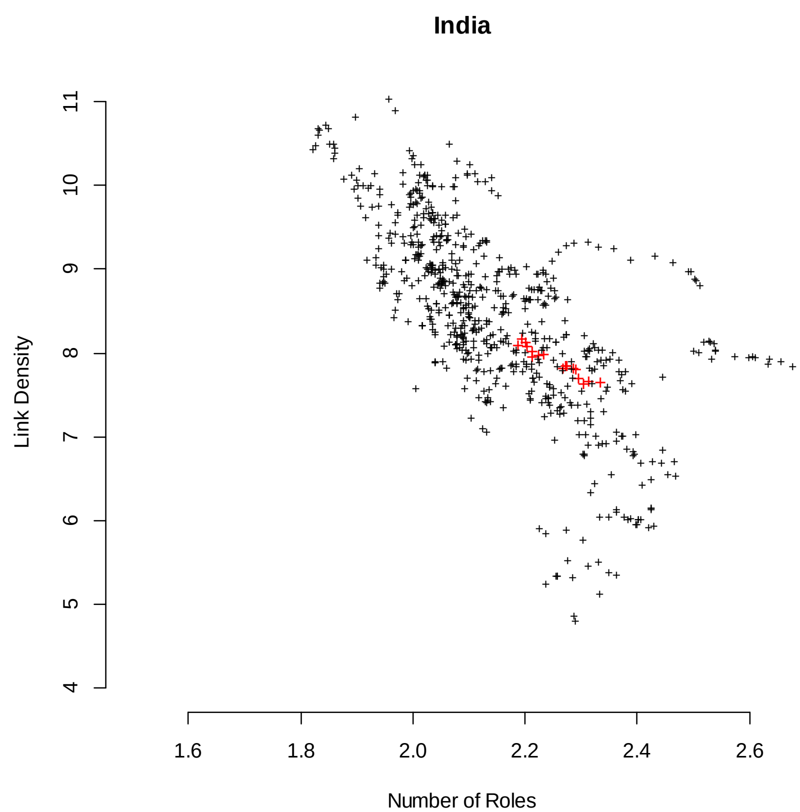

France
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6

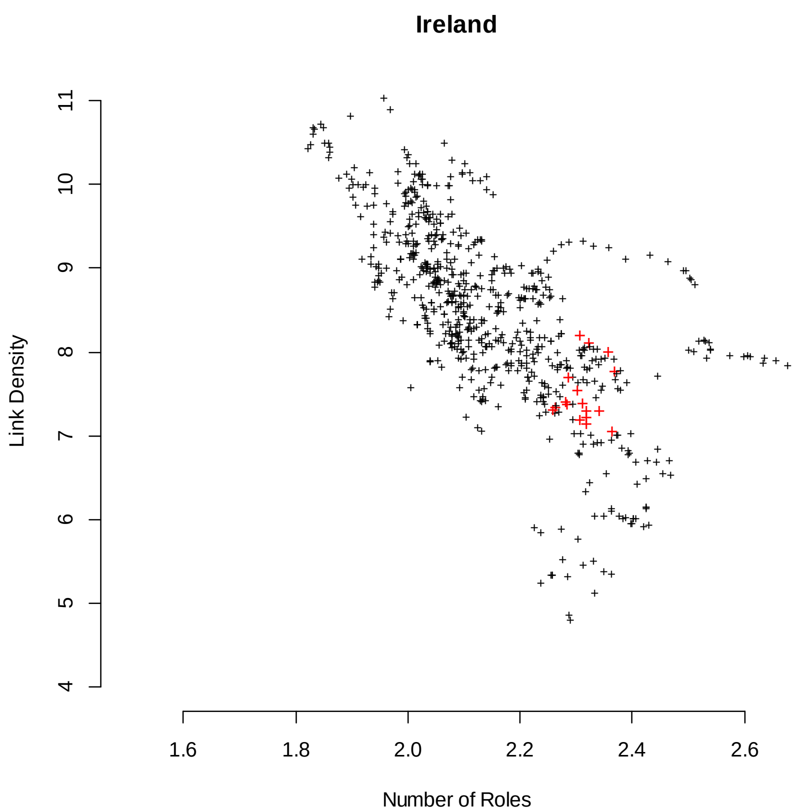

United Kingdom
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6

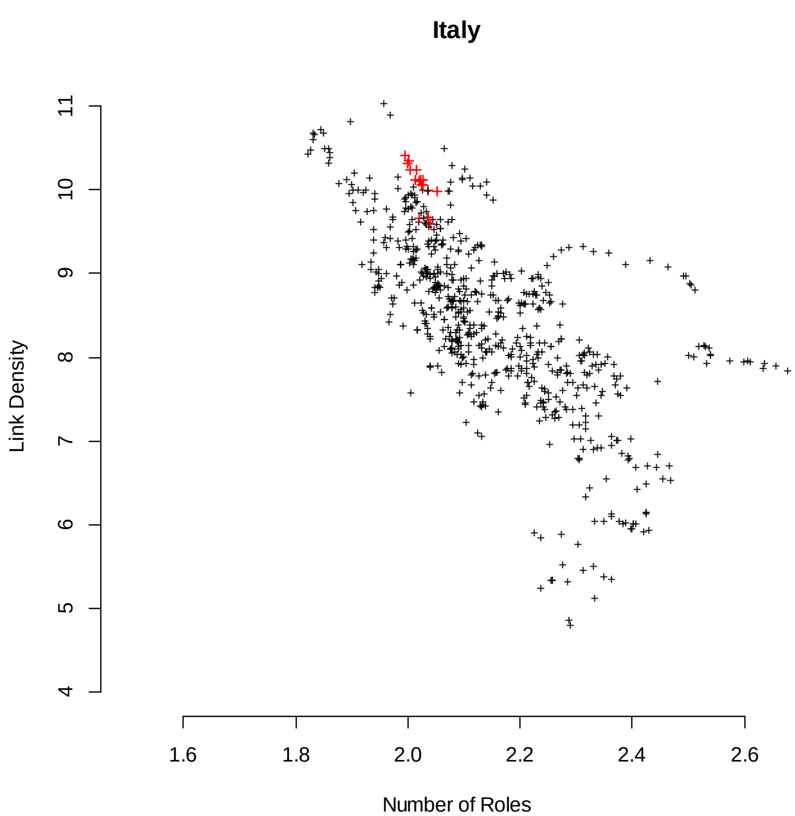

Greece
Link Density
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6
Number of Roles

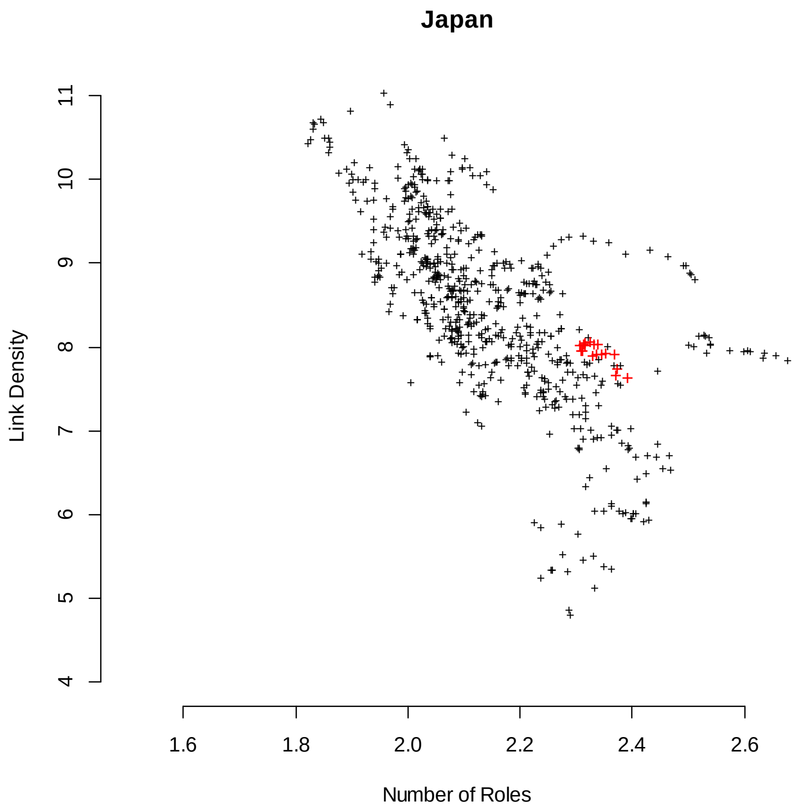

Hungary
Link Density
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6
Number of Roles


Indonesia
Link Density
Number of Roles
1.6
1.8
2.0
2.2
2.4
2.6
4
5
6
7
8
9
10
11


India
Link Density
Number of Roles
1.6
1.8
2.0
2.2
2.4
2.6
4
5
6
7
8
9
10
11


Ireland
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6


Italy
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6


Japan
Link Density
Number of Roles
4
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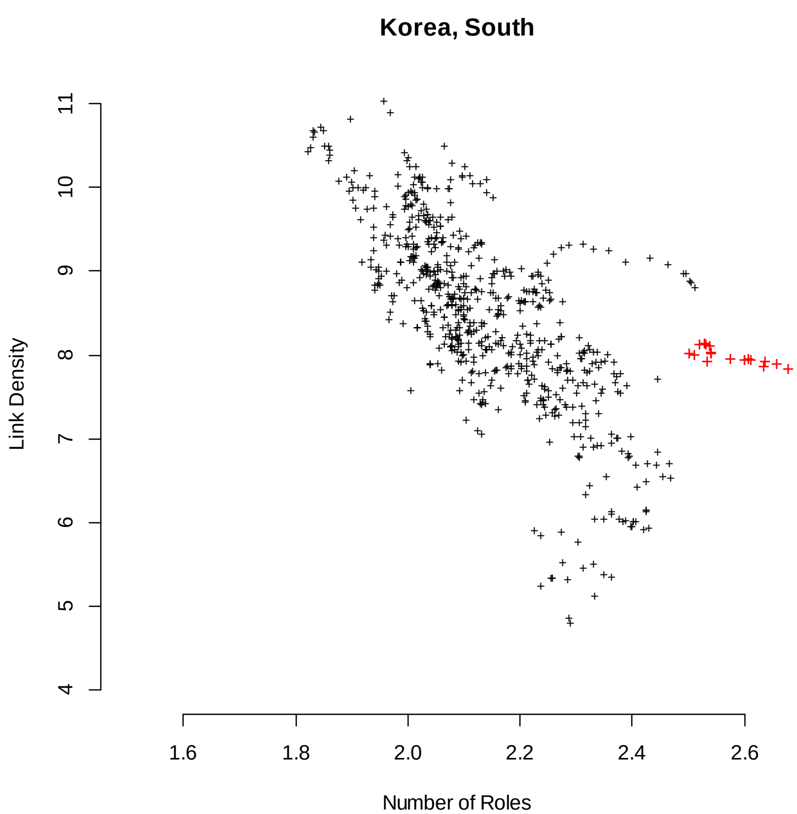
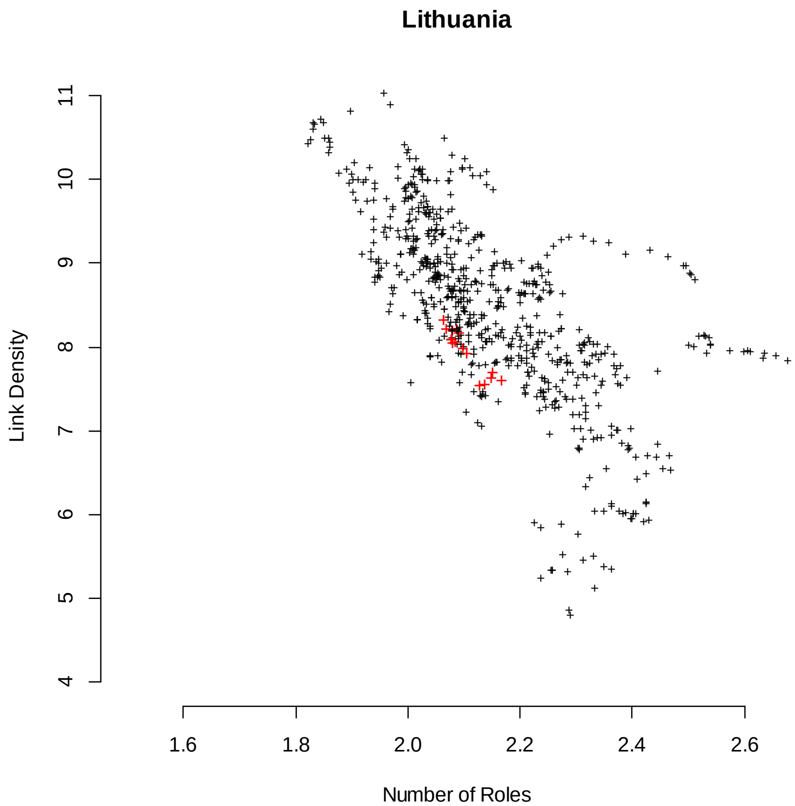
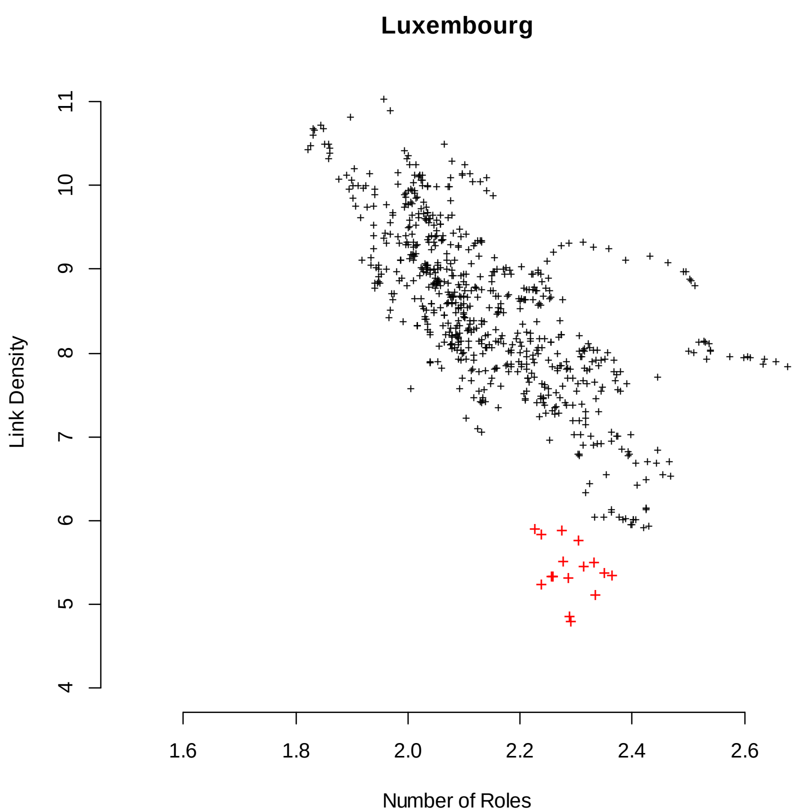
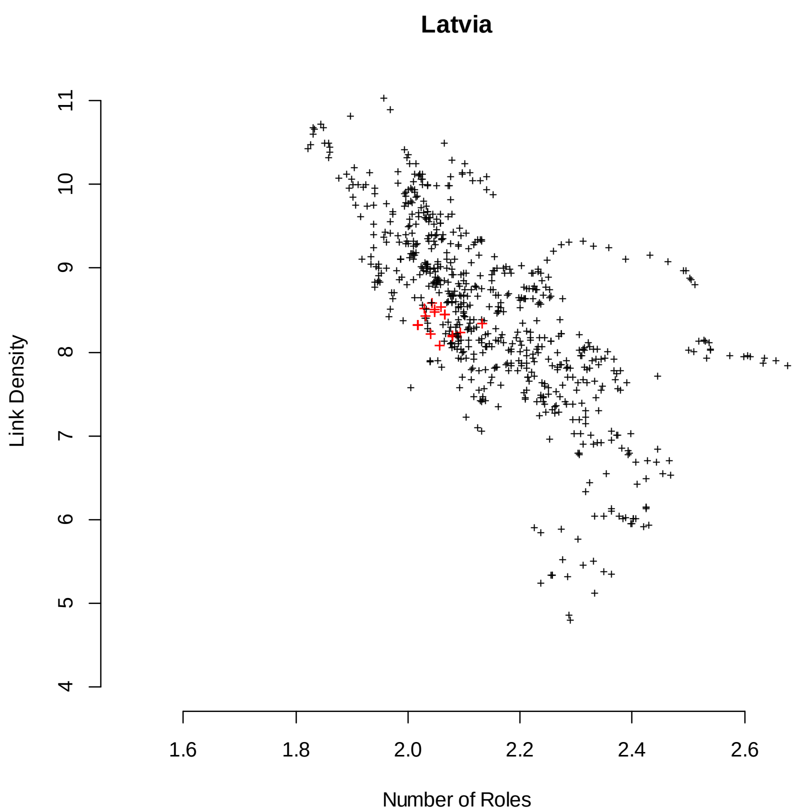
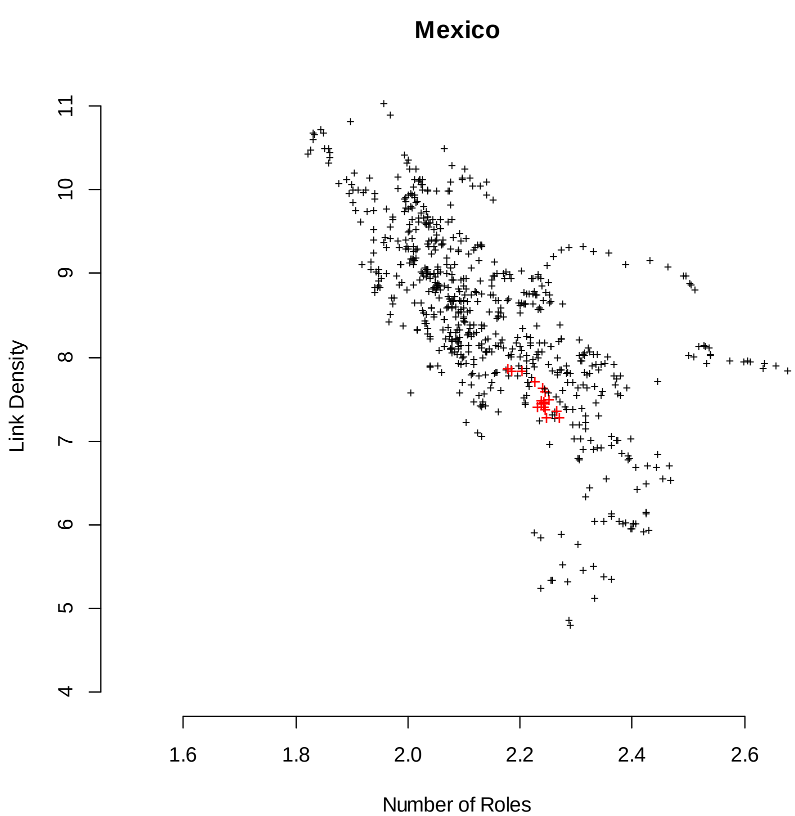
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6

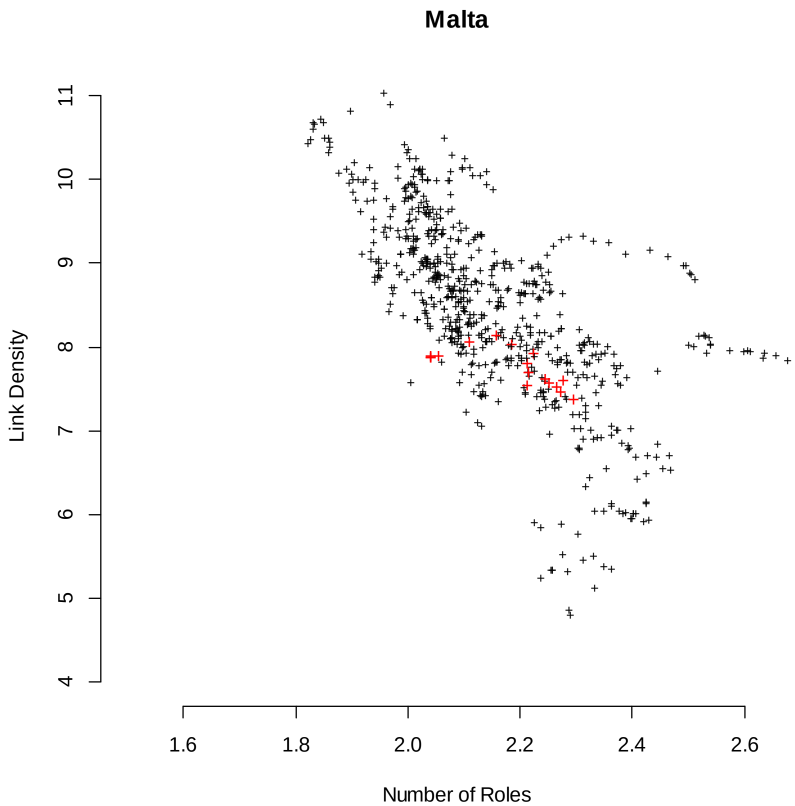

Korea, South
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6


Lithuania
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6

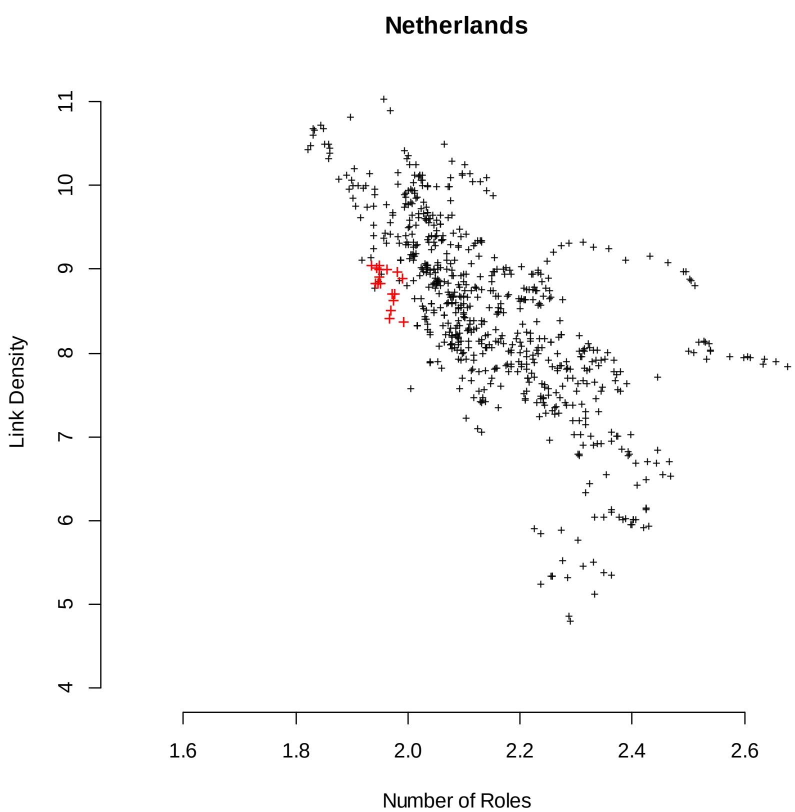

Luxembourg
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6


Latvia
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6

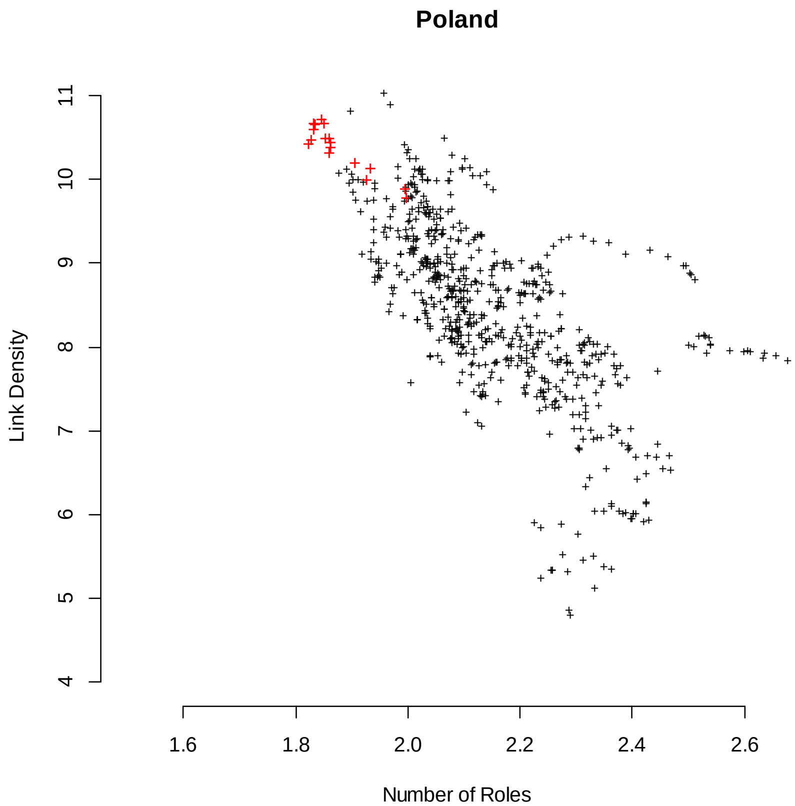

Mexico
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6



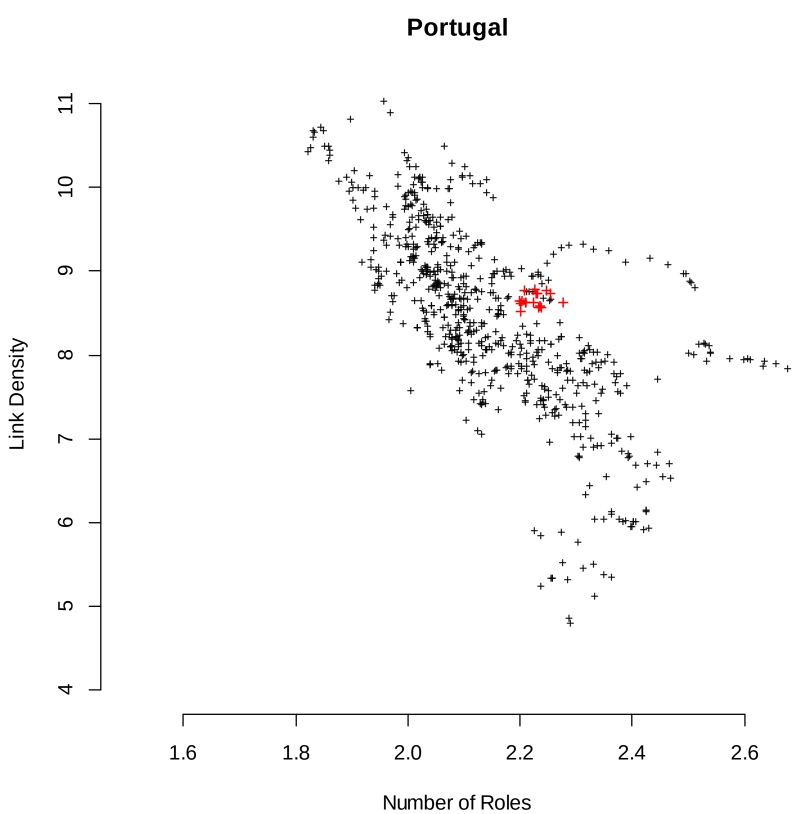
Malta
Link Density
Number of Roles
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6



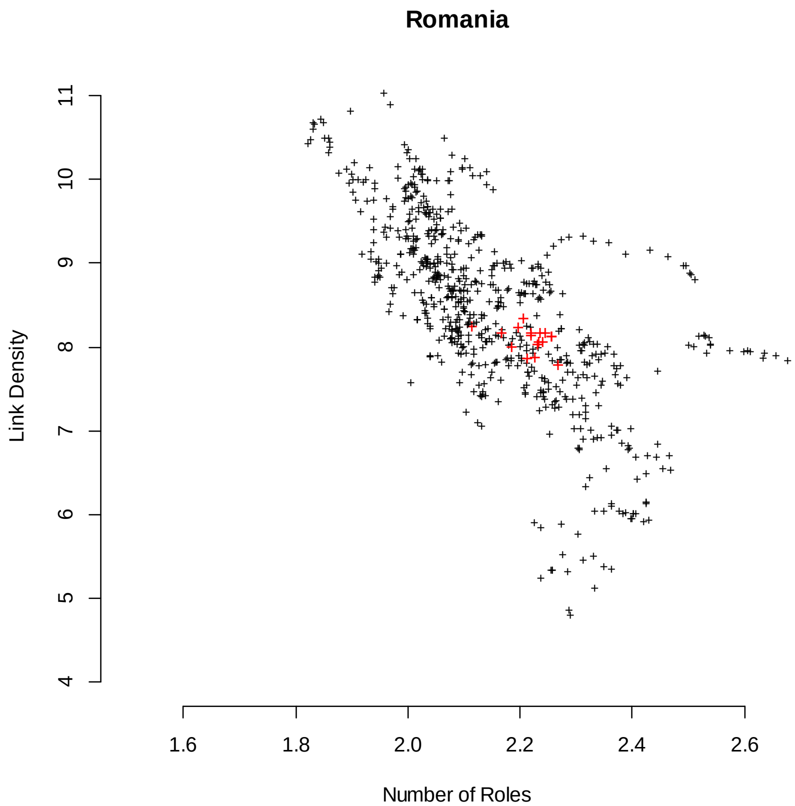
Netherlands
Link Density
Number of Roles
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6

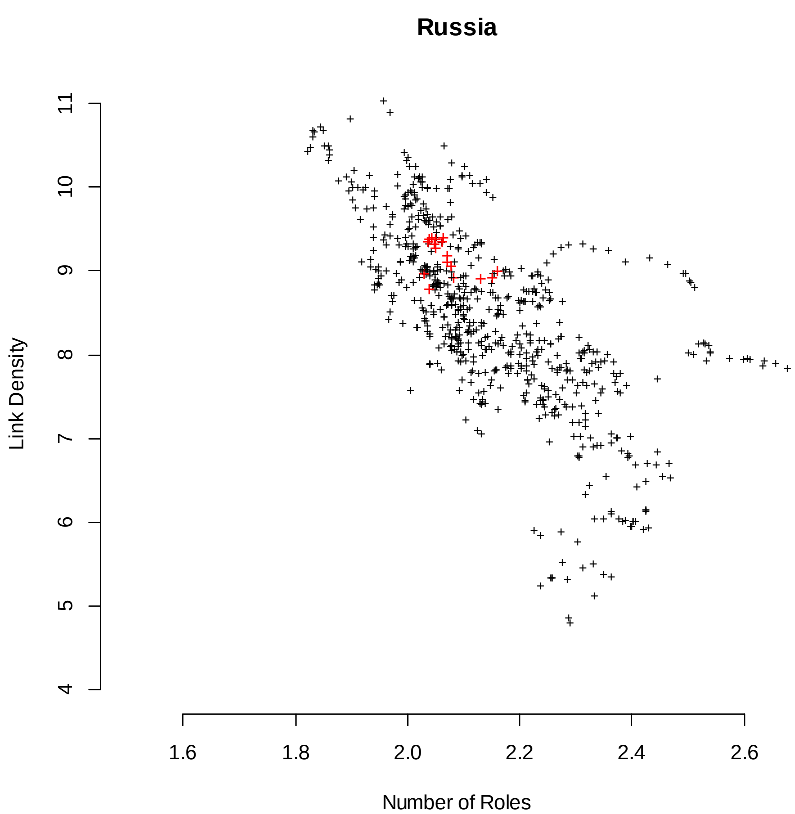


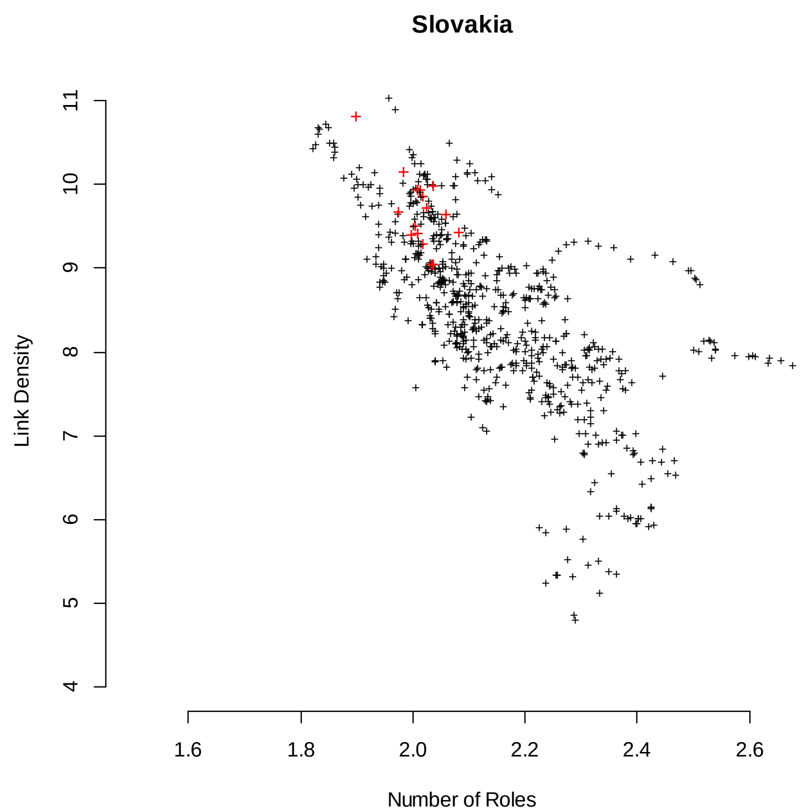
Poland
Link Density
Number of Roles
1.6
1.8
2.0
2.2
2.4
2.6
4
5
6
7
8
9
10
11

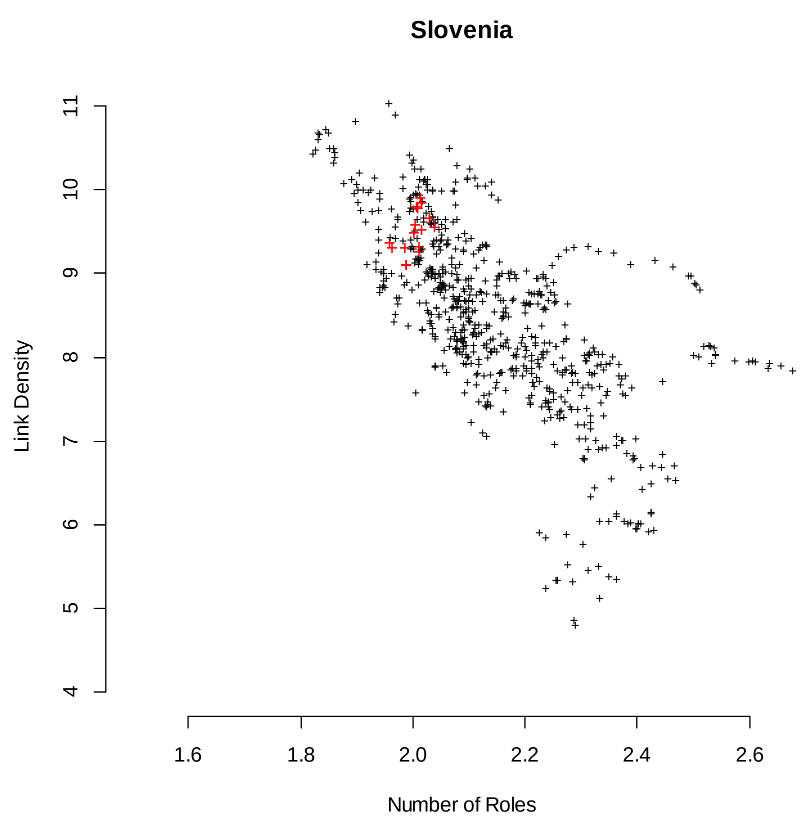


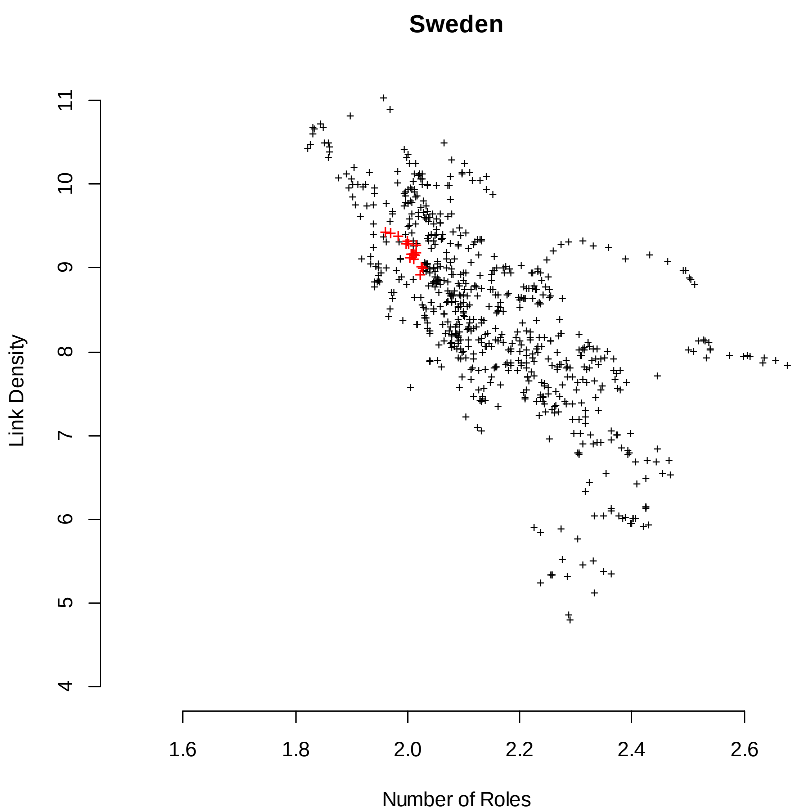
Portugal
Link Density
Number of Roles
1.6
1.8
2.0
2.2
2.4
2.6
4
5
6
7
8
9
10
11

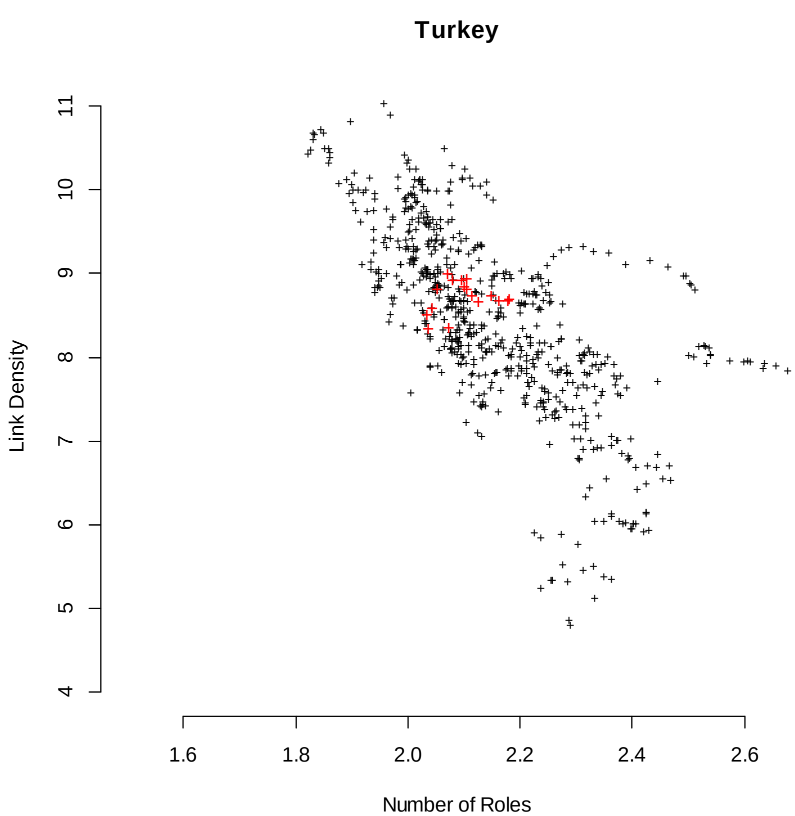

Romania
Link Density
Number of Roles
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6

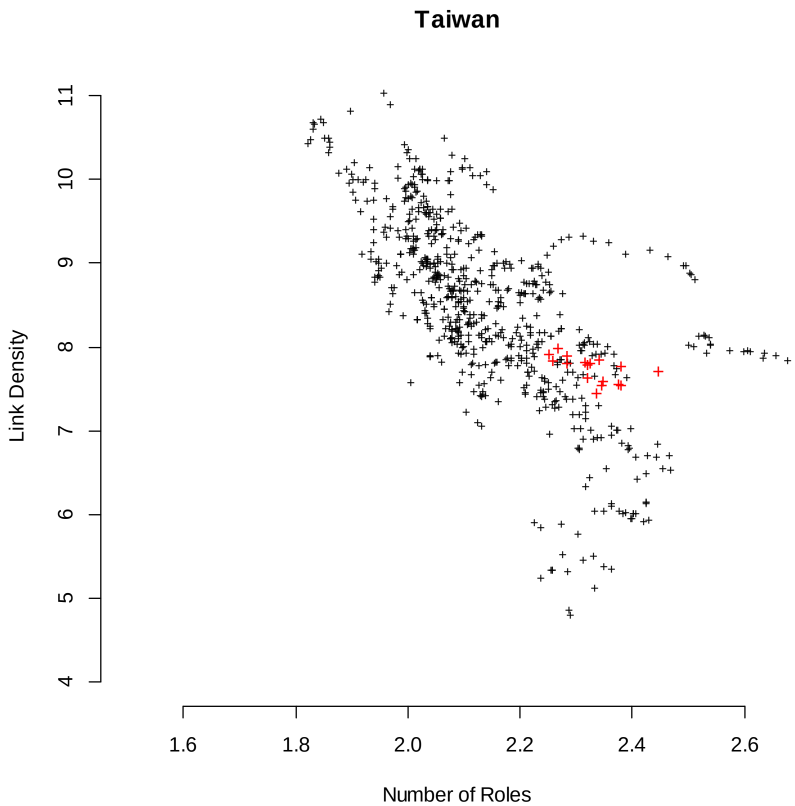

Russia
Link Density
Number of Roles
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6

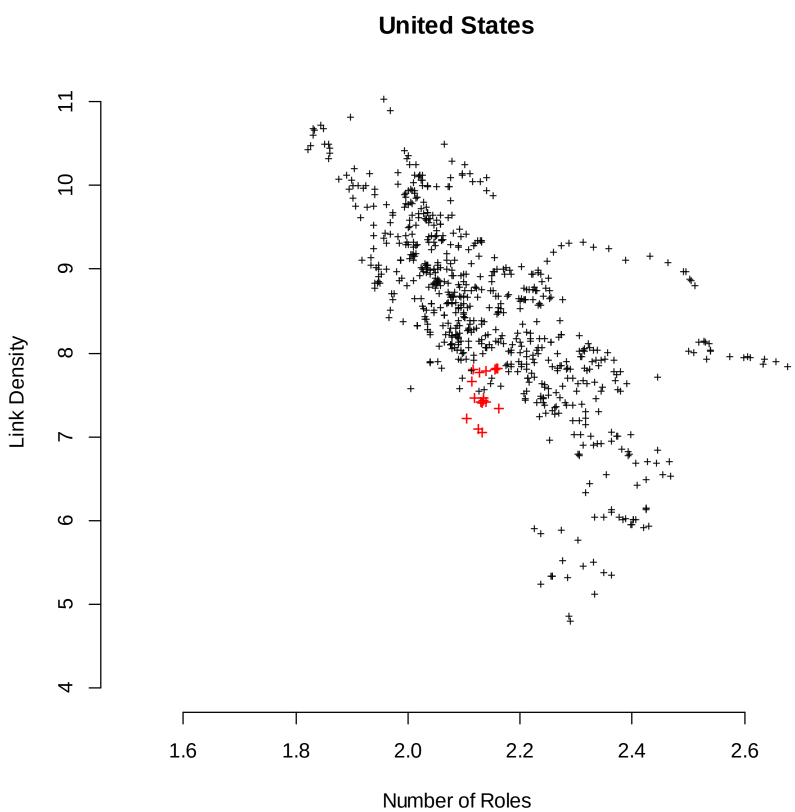

Slovakia
Link Density
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6
Number of Roles


Slovenia
Link Density
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6
Number of Roles


Sweden
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6


Turkey
Link Density
Number of Roles
4
5
6
7
8
9
10
11
1.6
1.8
2.0
2.2
2.4
2.6


Taiwan
Link Density
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6
Number of Roles


United States
Link Density
11
10
9
8
7
6
5
4
1.6
1.8
2.0
2.2
2.4
2.6
Number of Roles

References

Alcott, B., 2005, Jevons' paradox: Ecological Economics, v. 54, no. 1, p. 9–21, doi: 10.1016/j.ecolecon.2005.03.020.

Ayres, R., 1997, Comments on Georgescu-Roegen: Ecological Economics.

Ayres, R.U., 1998, Eco-thermodynamics: economics and the second law: Ecological Economics, v. 26, no. 2, p. 189–209, doi: 10.1016/S0921-8009(97)00101-8.

Batten, D.F., 1983, Spatial analysis of interacting economies: Martinus Nijhoff.

Benka, S.G., 2002, The energy challenge: Physics Today.

Blau, P.M., 1977, Inequality and Heterogeneity: Free Press.

Bonchev, D.G., and Rouvray, D.H., 2003, Complexity: Introduction and fundamentals:.

Boulding, K.E., 1955, The Malthusian model as a general system: Social and Economic Studies.

Boulding, K.E., 1973, The shadow of the stationary state: Daedalus,, doi: 10.2307/20024168.

Chontanawat, J., Hunt, L.C., and Pierse, R., 2008, Does energy consumption cause economic growth?: Evidence from a systematic study of over 100 countries: Journal of Policy Modeling, v. 30, no. 2, p. 209–220, doi: 10.1016/j.jpolmod.2006.10.003.

Costanza, R., 1980, Embodied Energy and Economic Valuation: Science, v. 210, no. 4475, p. 1219–1224, doi: 10.1126/science.210.4475.1219.

Costanza, R., and Herendeen, R.A., 1984, Embodied energy and economic value in the United States economy: 1963, 1967 and 1972: Resources and Energy, v. 6, no. 2, p. 129–163, doi: 10.1016/0165-0572(84)90014-8.

Gatlin, L.L., 1972, Information Theory and the Living System:.

Georgescu-Roegen, N., 1971, The Entropy Law and the Economic Process:.

Jevons, W.S., 1865, The Coal Question: An Inquiry concerning the progress of the nation and the probable exhaustion of our coal-mines: Macmillan and Co:.

King, C.W. World economy-wide energy expenditures and net energy metrics:, p. 1–17, doi: 10.1039/b000000x.

Leontief, W.W., 1986, Input-output Economics: Oxford University Press.

Madlener, R., and Alcott, B., 2009, Energy rebound and economic growth: A review of the main issues and research needs: Energy, v. 34, no. 3, p. 370–376, doi:

10.1016/j.energy.2008.10.011.

Malthus, T.R., 1798, An Essay on the Principle of Population:.

Maxwell, J.P. Energy Intensity Ratios as Net Energy Measures for Selected Countries 1978-2010.

Meadows, D.H., Meadows, D.L., Randers, J., and Behrens, W.W., 1972, The Limits to Growth: A report for the Club of Rome's Project on the Predicament of Mankind: Universe Books.

Mowshowitz, A., and Dehmer, M., 2012, Entropy and the Complexity of Graphs Revisited: Entropy, v. 14, no. 3, p. 559–570, doi: 10.3390/e14030559.

Pierce, J.R., 1980, An Introduction to Information Theory: Dover Publications.

Polimeni, J.M., and Polimeni, R.I., 2006, Jevons' Paradox and the myth of technological liberation: Ecological Complexity, v. 3, no. 4, p. 344–353, doi: 10.1016/j.ecocom.2007.02.008.

Schurr, S.H., 1984, Energy use, Technological Change, and Productive Efficiency: An Economic-Historical Interpretation: Annu. Rev. Energy, v. 9, no. 1, p. 409–425, doi: 10.1146/annurev.eg.09.110184.002205.

Shannon, C.E., 1948, A Mathematical Theory of Communication: The Bell System Technical Journal.

Stiglitz, J.E., 1980, A Neoclassical Analysis of the Economics of Natural Resources:.

Tainter, J., 1990, The Collapse of Complex Societies: Cambridge University Press.

Tainter, J.A., 2011, Energy, complexity, and sustainability: A historical perspective: Environmental Innovation and Societal Transitions, v. 1, no. 1, p. 89–95, doi: 10.1016/j.eist.2010.12.001.

Tainter, J.A., Allen, T., Little, A., and Hoekstra, T.W., 2003, Resource transitions and energy gain: contexts of organization: Conservation Ecology.

Theil, H., 1967, Economics and Information Theory:.

Theil, H., and Uribe, P., 1967, The Information Approach to the Aggregation of Input-Output Tables: The Review of Economics and Statistics, v. 49, no. 4, p. 451, doi: 10.2307/1928329.

Timmer, M., Erumban, A.A., Gouma, R., and Los, B., 2012, The world input-output database (WIOD): contents, sources and methods

Tribus, M., and McIrvine, E.C., 1971, Energy and information: Scientific American.

Ulanowicz, R.E., 1997, Ecology, the Ascendent Perspective: Columbia University Press.

Ulanowicz, R.E., 2002, The balance between adaptability and adaptation: Biosystems, v. 64, no. 1-3, p. 13–22, doi: 10.1016/S0303-2647(01)00170-8.

Ulanowicz, R.E., and Hirata, H., 1984, Information theoretical analysis of ecological networks: dx.doi.org, v. 15, no. 3, p. 261–270, doi: 10.1080/00207728408926559.

Ulanowicz, R.E., Goerner, S.J., Lietaer, B., and Gomez, R., 2009, Quantifying sustainability: Resilience, efficiency and the return of information theory: Ecological Complexity, v. 6, no. 1, p. 27–36, doi: 10.1016/j.ecocom.2008.10.005.

Zorach, A.C., and Ulanowicz, R.E., 2003, Quantifying the complexity of flow networks: How many roles are there?: Complexity, v. 8, no. 3, p. 68–76, doi: 10.1002/cplx.10075.